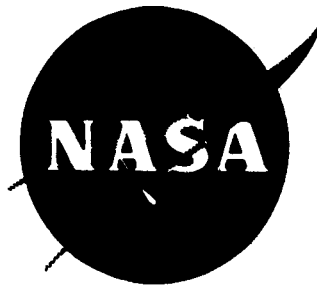


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**STUDY OF CAPACITORS
FOR STATIC INVERTERS AND CONVERTERS**

By J. F. Scoville

**PREPARED FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION**

CONTRACT NAS3-2788

GENERAL  ELECTRIC

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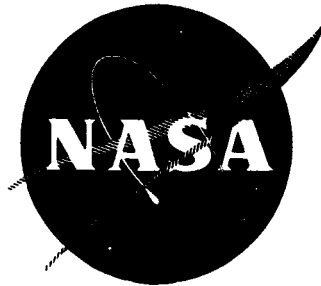
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FINAL REPORT

**STUDY OF CAPACITORS
FOR STATIC INVERTERS AND CONVERTERS**

By J. F. Scoville

PREPARED FOR
NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

OCTOBER 30, 1964

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TECHNICAL MANAGEMENT
NASA-LEWIS RESEARCH CENTER
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TITLE					
Study of Capacitor for Static Inverters and Converters.					
ABSTRACT Objectives of this study of capacitors for application in aerospace static inverters and converters were to determine state-of-the-art capacitors, their AC characteristics, safe operating voltages and temperature consistent with reliability and weight objectives. Analysis of operation and losses of commutating capacitors. Capacitance change and dissipation factors for polycarbonate, metallized paper and tantalum capacitors are presented					
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CONCLUSIONS					
Polycarbonate film dielectric capacitors are considered state-of-the-art. Low dissipation factors and capacitance stability of polycarbonate capacitors were obtained in tests over an ambient temperature range from cycles. Appreciable size and weight reductions of commutating and load filter capacitors in aerospace static inverters and converters may be realized with the use of polycarbonate capacitors.					

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SUMMARY

This is the final report for the "Study of Capacitors for Static Inverters and Converters". The objectives of this study were: (1) To determine state-of-the-art capacitors for use in aerospace static inverters and converters: and (2) Determine A.C. characteristics of these capacitors to facilitate selection of ratings and limits for such factors as safe operating voltage, temperature rise, size, weight and reliability.

Investigations were limited to those capacitors suitable for use in static inverters and converters operating in a space environment with these ratings:

Input: 25 to 105 volts, D.C.

Output: 0.1 to 10.0 kilowatts, 115/200 volts, 3 phase, 400 cps

An industry survey, conducted in the early part of this study, indicated that state-of-the-art capacitors are polycarbonate for film capacitors and tantalum for electrolytic capacitors. Metallized polycarbonate, polycarbonate/foil, and metallized paper capacitors were tested to determine capacitance and dissipation factor variations versus temperature and frequency. Measurements were taken in -55°C to $+85^{\circ}\text{C}$ ambients with excitation frequencies from 0.4 to 10.0 kilocycles and a few measurements were taken with excitation frequencies extending to 80 kilocycles in a 25°C ambient.

In general, polycarbonate capacitors exhibit capacitance and dissipation factor value variations of less than half that for metallized paper capacitors over the temperature and frequency range of the tests.

The small dissipation factors (i.e. power losses) of polycarbonate capacitors facilitates smaller size and weight capacitors with lower hot spot temperatures than metallized paper capacitors in some A.C. applications.

INTRODUCTION

Lack of adequate alternating current data and characteristics of paper and film dielectric capacitors contribute to the difficulty of properly applying capacitors to aerospace static inverters and converters. Improper application of capacitors in these equipments could result in appreciable penalties in weight and reliability factors, both of which are at a premium in equipment operating in space.

A need for the "Study of Capacitors for Static Inverters and Converters" was influenced by the stringent requirements imposed on capacitors by the operating nature of the equipment in a space environment and by the general lack of capacitor A.C. characteristics and data.

In static inverters, appreciable heat generation within capacitors is caused by alternating currents from ripple, commutation and output voltages. Heat transfer is generally limited to conduction across the capacitor mounting surface to radiator systems on space vehicles.

The purpose of this study is to obtain the alternating current characteristics and data of state-of-the-art capacitors, for application in aerospace static inverters and converters. These characteristics will facilitate proper selection of ratings and limits for such factors as safe operating voltage, temperature rise, size, weight and reliability.

State-of-the-art metallized polycarbonate and extended foil polycarbonate capacitors from several manufacturers were evaluated for capacitance and dissipation factor variation with temperature and frequency. Evaluation of A.C. characteristics for a few metallized paper capacitors was included for reference purposes. Similarly, a very limited quantity of state-of-the-art tantalum capacitors was evaluated, because of availability of adequate A.C. characteristics and data for this type of capacitor.

Capacitor alternating current characteristics were determined by impedance bridge measurements. Some of these capacitors were also tested in a calorimeter to measure power losses. Results from these calorimeter tests were utilized as correction factors for the capacitor dissipation factor obtained by the impedance bridge. This method of testing, although more time consuming, is considered more accurate for determining dissipation factors that were often below the resolution of most commercial capacitor bridges.

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It is hoped that the commutating capacitor analyses of operation and losses contained in this report will provide capacitor manufacturers with a better understanding of this type of application. Capacitance and dissipation factor test data presented in this report is expected to facilitate the proper capacitor selection by equipment designers for A.C. application in aerospace inverter s and converters.

1.0 Scope of Study

The lack of adequate alternating current characteristics and data has caused considerable difficulty for equipment designers in selection of capacitors for application in static inverters and converters.

Objectives of this study were: (1) To determine state-of-the-art capacitors for aerospace inverter applications; and (2) to determine state-of-the-art capacitor A.C. characteristics to facilitate selection for the inverter applications.

In accomplishing these objectives, this study included a brief analysis of commutation capacitors, conduction of an industry survey for state-of-the-art capacitors and testing of selected capacitor types. Testing of capacitors was limited to capacitance and dissipation factor variations with temperature and frequency and a life test.

This study was not primarily concerned with capacitor D.C. characteristics. However, one supplier of polycarbonate film lists typical values of insulation resistance in 25°C ambient of 250,000 megohm-microfarads and 20,000 megohm-microfarads in 125°C ambient. This manufacturer also lists a typical dielectric absorption of 0.2% for polycarbonate as tested in accordance with MIL-C-19978B. Specific capacitor application requirements such as vibration, shock, radiation effects and hermetic seals, were not considered within the scope of this study, but these requirements were used as guidelines in the industry survey.

1.1 Discussion of Capacitor Functions

Capacitors in aerospace static inverters and converters provide these basic functions: (1) D.C. Filter; (2) A.C. Filter; and (3) Commutation. Generally, static inverters that employ silicon controlled rectifiers as static switches require all three capacitor functions and inverters using transistors as static switches require only the filter functions.

Commutating capacitors in conjunction with commutating reactors are used for electrical energy storage to effect commutation of load current from one silicon controlled rectifier to another. The stored electrical energy in these commutating components furnish sufficient back biasing voltage to a rectifier that has been conducting to turn it off when a second rectifier is turned on. The analysis contained in Appendix A explains this functional operation in more detail.

Alternating current filter capacitors are normally required with reactors in the output circuits of static inverters to shape voltage and current waveforms from quasi square-wave, caused by the alternate static switching, to sinusoidal waveforms. Generally, these inductive-capacitive (L-C) filters employ capacitors connected in series and in parallel with the load as shown in Figure 1.

Direct current filter capacitors are usually employed in input circuits of static inverters and output circuits of converters. Their main purpose is storage of electrical energy and release thereof for reducing or regulating source voltage variations from pulse loading.

1.2 Application Considerations

Environments

Potential environments that capacitors may encounter in aerospace static inverter and converter applications are major considerations in the selection of capacitor materials. Environmental conditions, assumed to be representative for a variety of equipment design applications, selected for a state-of-the-art survey in this study are:

- a) Heat Sink Ambient Temperature Range: -55°C to $+85^{\circ}\text{C}$.
- b) Capacitor heat transfer by conduction to heat sink.
- c) Shocks of 35 g's in half sine wave shocks for 0.008 seconds.

- d) Vibration: Sinusoidal

<u>Frequency (CPS)</u>	<u>Force or Displacement</u>
5-20	0.3 inches double amplitude
20-100	5 g's
100-500	10 g's
500-2000	15 g's

- e) Radiation:
 - 5×10^{-12} NVT Fast Neutrons/cm²
 - 5×10^{-7} RADS (carbon) Gamma Particles

- f) Hermetically sealed construction to protect capacitor from effects of sublimation from temperature-pressure conditions.

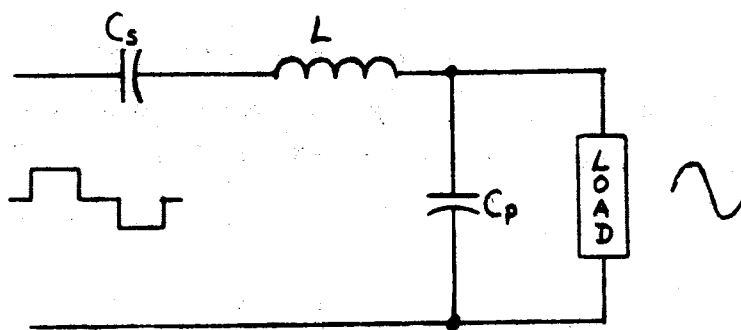


FIGURE 1

A.C. FILTER CONFIGURATION

C_s - Series Capacitor

C_p - Parallel Capacitor

Use of these environment considerations in the survey was utilized to facilitate the usefulness of this study to equipment designers of aerospace static inverters and converters.

Power Source

Types of power sources considered for the inverters and converters are: a) Batteries, b) Solar cells, c) Thermionic converters, d) Fuel cells, and e) Rotating D.C. generators.

Power source characteristics, particularly voltage regulation, ripple and transient voltages are important considerations in selection of capacitors for equipment designs.

Source voltage range used is 25 to 105 volts D.C. However, with present and near future power sources it appears that source voltage ranges from 25 to 35 volts, 50 to 65 volts and 90 to 105 volts offer a representative coverage within the range from 25 to 105 volts. These three (3) discrete source voltage ranges were used for the capacitor survey.

A second power source consideration is ripple. A peak-to-peak ripple of plus and minus 10 per cent of the maximum steady state voltage was chosen as being representative for various applications of D.C. input filter capacitors. Maximum frequency of the ripple voltage was considered to be 25 kilocycles and is representative of other unfiltered static inverter equipment operating from the same power source.

The third power source consideration is voltage transients. Removal of loads near the end of a transmission line can cause transient overvoltage conditions. In this study, transient overvoltage of 150 per cent for durations up to 100 milliseconds are considered representative for some aerospace static inverter applications of D.C. filter capacitors.

Load

Load characteristics, such as transient overvoltage from load removal and overcurrents are also important considerations in the selection of A.C. filter capacitors for equipment designs. Transient overvoltage of 125 per cent of rated voltage for a duration of 5 cycles of the rated 400 cycle base was chosen to be representative of equipment applications. Overcurrents of

twice-rated load current for 5 seconds was also considered representative of equipment applications. However, output inductive-capacitive (L-C) filter configurations and power factor of the load during overcurrent conditions have a relationship to the peak currents and voltages of the capacitors. Two (2) rated rms voltage values were selected for the capacitor survey. These are 135 and 270 volts rms, 420 cycles. Dielectric voltage rating for these capacitors were chosen to be 600 and 1000 volts respectively to accommodate peak transient voltage conditions. The 420 cycle rating was chosen to provide adequate margin from overheating during inverter operation at 400 ± 20 cps.

Three (3) discrete output ranges within the 0.1 to 10.0 kilowatt output power range for the static inverters considered were: (1) 0.1 to 0.5 kilowatts; (2) 0.5 to 2.0 kilowatts; and (3) 2.0 to 10.0 kilowatts.

1.3 Selection of Capacitor Values for an Industry Survey

Commutating Capacitors

Analysis of the operation of commutating capacitors and design experience with static inverters has shown that a relationship exists between the value of capacitor and characteristics of the static switching device. The characteristics of the switching device that enter this relationship to capacitor value are magnitude of load current flowing through the switching device at the end of each half cycle (i.e., start of commutation) and device turn-off time.

Four (4) silicon controlled rectifiers, with current ratings that are capable of handling the inverter power output range in this study, were chosen for sizing the commutating capacitors. Turn-off times for these silicon controlled rectifiers are either vendor guaranteed or test selected by vendor. Values of current flowing through the silicon controlled rectifiers at the end of the half cycle are based on safe thermal limits for these devices for 180 degree conduction angles.

The design equations used for sizing the commutating capacitors are:

$$C = \frac{5.22 I_o t_{off}}{E_{min.}} ; \quad I_p = \frac{1.37 I_o E_{max.}}{E_{min.}}$$

Where I_o is current flowing through the silicon controlled rectifier at the end of the half cycle, t_{off} is turn-off time for the rectifier, E_{max} and E_{min} are maximum and minimum steady state source voltages respectively and I_p is peak amperes capacitor current.

These equations are derived in Appendix A of this report.

Commutating capacitors, selected from the analysis, shown in Appendix A, for the survey were:

<u>Capacitance (mfd)</u>	<u>D.C. Voltages</u>
5	35, 65 and 105
15	35, 65 and 105
50	35, 65 and 105

These capacitance values, when used singly or in multiples, are capable of covering the inverter output power range for this study.

A.C. Filter Capacitors

Inverter output voltage is 115/200 volts, 400 cycles per second. Filter capacitors connected in parallel with the load, as shown in Figure 1, have voltage ratings consistent with the load voltage. Voltage ratings of filter capacitors connected in series with the load or reactors are dependent on inverter waveforms, filter design and load currents.

The following capacitors were selected for the survey:

<u>Capacitance (mfd)</u>	<u>RMS Voltage</u>
1-3	135 and 270
8-10	135 and 270
50-60	135 and 270

These capacitance values, used singly or in multiples will accommodate many equipment designs within the output power range of this study.

D.C. Filter Capacitors

Discrete source voltage levels, establish voltage ratings of the input filter capacitors. Two (2) capacitance ranges were selected for the survey:

<u>Capacitance (ufd)</u>	<u>Voltages</u>
1000-1500	35, 65 and 105
10,000-15,000	35, 65 and 105

These capacitance values, or multiples thereof, will accommodate many equipment designs within the inverter and converter ratings for this study.

2.0 Capacitor Survey

Filter and commutating capacitor specifications, similar to the one contained in Appendix A for commutation capacitors, were submitted to a large number of capacitor manufacturers as a part of the industry survey. Requests to these manufacturers to furnish technical and cost proposals to these specifications resulted in formal proposals from six (6) manufacturers and incomplete proposals from five (5) additional manufacturers.

From the responses to the survey and visitations to five (5) capacitor manufacturers, it was apparent that polycarbonate capacitors were considered state-of-the-art for film capacitors and tantalum for electrolytics.

2.1 Results of Survey

Commutating Capacitors

The following four (4) types of capacitors were recommended by capacitor manufacturers for the commutating capacitor applications:

- A) Metallized polycarbonate film
- B) Polycarbonate film and foil
- C) Paper-Mylar* and foil
- D) Paper and foil

The evaluation criteria variations encountered in the survey were:

*Trademark of the E. I. Dupont Company

- 1) Volume to capacitance ratio of:
0.22 to 1.85 in $\frac{3}{\text{ufd}}$ for the 35 and 65 Volt ratings
1.05 to 4.8 in $\frac{3}{\text{ufd}}$ for the 105 Volt rating
- 2) Weight to capacitance ratio of:
0.015 to 0.18 pounds/ufd for the 35 and 65 Volt ratings
0.058 to 0.34 pounds/ufd for the 105 Volt rating
- 3) Volume to energy storage ratio of:
44.5 to 411 in $\frac{3}{\text{joule}}$ for the 35 and 65 Volt ratings
85 to 374 in $\frac{3}{\text{joule}}$ for the 105 Volt rating

A. C. Filter Capacitors

Capacitor manufacturers recommended the following four (4) types of capacitors for the A.C. filter capacitor applications:

- A) Metallized polycarbonate film
- B) Polycarbonate film and foil
- C) Paper-Mylar and foil
- D) Paper and foil

Evaluation criteria variations encountered were:

- 1) Volume to capacitance ratio:
0.21 to 5.35 in $\frac{3}{\text{ufd}}$ for the 135 V rms ratings
0.5 to 7.65 in $\frac{3}{\text{ufd}}$ for the 270 V rms rating
- 2) Weight to capacitance ratio:
0.018 to 0.33 pounds/ufd for the 135 V rms ratings
0.035 to 0.535 pounds/ufd for the 270 V rms rating
- 3) Volume to energy storage ratio:
10.3 to 29.6 in $\frac{3}{\text{joule}}$ for the 135 V rms ratings
6.5 to 15.6 in $\frac{3}{\text{joule}}$ for the 270 V rms rating

D.C. Filter Capacitance

Recommendations for the D.C. filter capacitor applications included three (3) types:

- A) Sintered tantalum
- B) Tantalum foil
- C) Polycarbonate film

Reservations concerning the specified peak to peak ripple voltage of 10 per cent of the D.C. voltage ratings accompanied many of the manufacturer's recommendations for usage of tantalum electrolytic capacitors.

Slightly different evaluation criteria are used for the D.C. filter capacitors. The volume and weight to volt-capacitance ratios were favored because the volume to capacitance for electrolytics varies approximately with voltage. Film capacitors have broad discrete steps of volume and weight to volt-capacitance ratio.

The volume to voltage capacitance ratios determined from the survey for these types of capacitors were:

<u>Type</u>	<u>Cubic Inches/Volt-Microfarad</u>
125°C, Tantalum porous anode	$3.0-4.0 \times 10^{-5}$
125°C, Tantalum foil	$11.0-13.0 \times 10^{-5}$
Polycarbonate film	$100-185 \times 10^{-5}$

Only 125°C tantalum capacitors were considered in the survey to facilitate temperature derating for reliability purposes.

The effective series resistance (ESR), in 25°C ambient and with 120 cycle/second voltage, is within the same order of magnitude (i.e., 1 to 10 ohms) for both types of tantalum capacitors. The ESR of polycarbonate film capacitors is at least one order of magnitude smaller than the tantalum electrolytics.

Weight to voltage-capacitance ratio for these three types of capacitors are:

<u>Type</u>	<u>Pounds/Volt-Microfarad</u>
Sintered Tantalum	2.5-10.0 x 10 ⁻⁶
Tantalum Foil	5.0-16.8 x 10 ⁻⁶
Polycarbonate Film	87.5-265 x 10 ⁻⁶

Volume to energy storage ratio variations are:

<u>Type</u>	<u>Cubic Inches/joule</u>
Sintered Tantalum	0.8 to 1.8
Tantalum Foil	0.75 to 4.06
Polycarbonate Film	44.5 to 120.0

2.2 Selection of Capacitors for Experimental Testing

Capacitor selection for experimental tests was based on the following considerations:

- a) Low volume and weight to capacitance ratios
- b) Low dissipation or power factor
- c) Adequate temperature capability to enable temperature derating for reliability purposes

Although the capacitor survey was conducted with specifications for several ranges of capacitances and voltages, economies could be realized by selecting commutating and A.C. filter capacitance values of 1 to 5 microfarads for the experimental tests. Packaging of larger capacitance values will be influenced by the power factor of the capacitor, frequency, voltage waveform, materials and physical environmental requirements.

Commutating and A.C. Filter

Metallized polycarbonate film capacitors having capacitance values of 1, 2, 2.5 and 3 microfarads with D.C. voltage ratings of 200, 300 and 400 volts were selected from four (4) manufacturers.

Polycarbonate film and foil capacitors having capacitance values from 1, 2, 3 and 5 microfarads with D.C. voltage ratings of 150, 200, and 400 volts were selected from four (4) manufacturers.

Metallized paper capacitors with capacitance values of 2 to 3 microfarads and D.C. voltage ratings of 200 and 400 volts were selected from two (2) manufacturers.

Other film type capacitors that were not selected for experimental test evaluation are:

- A) Teflon*--These capacitors have adequate temperature capabilities and low dissipation factors but the size, weight and cost penalties compared with polycarbonate or paper capacitors offset any advantages.
- B) Mylar--Capacitors of this type are comparable to the size and weight of polycarbonate capacitors but have appreciable power factors between 85°C and 125°C.
- C) Polystyrene--These capacitors have characteristics that are comparable or better than polycarbonate capacitors except for the temperature limitation of 85°C.

D.C. Filter

Since tantalum electrolytic capacitors are considered state-of-the-art and A.C. characteristics for these capacitors are generally known, only a very limited quantity of sintered and foil types were obtained for reference evaluation.

Sintered tantalum capacitors selected have ratings of 22 microfarads, 100 volts D.C., 125°C.

Tantalum foil electrolytic capacitors were selected with ratings of 36 microfarads, 150 volts D.C., 125°C.

Voltage ratings greater than 100 volts D.C. for sintered tantalum electrolytics are available by series element arrangements with associated penalties in size and weight.

Aluminum electrolytics were not considered because of the 65°C and 85°C temperature rating limitations.

2.3 Tubular Film Capacitor Comparisons

A comparison of tubular capacitor sizes and weights by type is presented in Table I. In the 400 VDC ratings, the ratio of the

*Trademark of the E. I. DuPont Company

Tabulation of Tubular Film Capacitor Sizes and Weights

Capacitor Identification No.	Rating		Type	Vol/Cap (in/uF)	Average Vol./uF/Type	Wgt/Cap (lb./F)
	400 VDC	200 VDC				
1A-1E	1 uF		MPC	0.91	0.93	.063
2A-2E	2 uF		MPC	0.94		.062
3A-3E	2.5 uF		MPC	1.03		.059
5A-5E	2 uF		MPC	.84		.053
7A-7E	2 uF		MP	.89	0.80	.064
8A-8E	2 uF		MP	.71		.052
9A-9E	1 uF		PCF	2.06	2.06	.145
12A-12E		3 uF	MPC	0.35	0.29	.023
13A-13E		3 uF	MPC	0.28		.018
14A-14E		3 uF	MPC	0.56*		.036
15A-15E		3 uF	MPC	0.24		.017
4A-4E		2 uF	MP	0.22	0.21	.018
16A-16E		3 uF	MP	0.21		.016
10A-10E		2 uF	PCF	0.93	0.93	.069

Key: MPC - Metallized Polycarbonate
 MP - Metallized Paper
 PCF - Polycarbonate/Foil

*Omitted in the Average Vol/uF/Type
 figure

TABLE I

average volume/capacitance of metallized polycarbonate to metallized paper capacitors is 116 percent and similarly the ratio for the 200 VDC ratings is 138 percent. This 22 percent increase in volume/capacitance ratio from the 400 VDC to the 200 VDC ratings may be attributed to a minimum polycarbonate film thickness availability limitation.

The volume/capacitance ratio between polycarbonate/foil and metallized paper capacitors is 250 percent for the 400 VDC ratings and 450 percent for the 200 VDC ratings. From these large ratios, it appears that the foil thickness may approach the polycarbonate film thickness.

The pounds/ capacitance for metallized polycarbonate is approximately the same as for metallized paper capacitors. Larger physical size of the polycarbonate capacitors, compared with metallized paper, account for the larger pounds/capacitance figure.

3.0 Capacitor Experimental Tests and Results

Three (3) types of capacitor tests were conducted during this study: (1) Capacitance and dissipation factor; (2) Commutating capacitor; and (3) Life.

Capacitance and dissipation factor test data were obtained as a function of frequency and temperature for metallized polycarbonate, metallized paper, polycarbonate/foil and tantalum electrolytic capacitors. Commutating capacitor tests were conducted with a metallized polycarbonate capacitor and an analysis of the capacitor power losses was made utilizing data obtained from the capacitor and dissipation factor tests. A life test of the three types of capacitors was conducted for 1000 hours in an 85°C ambient and 370 hours in 125°C ambient.

3.1 Capacitance and Dissipation Factor Tests and Results

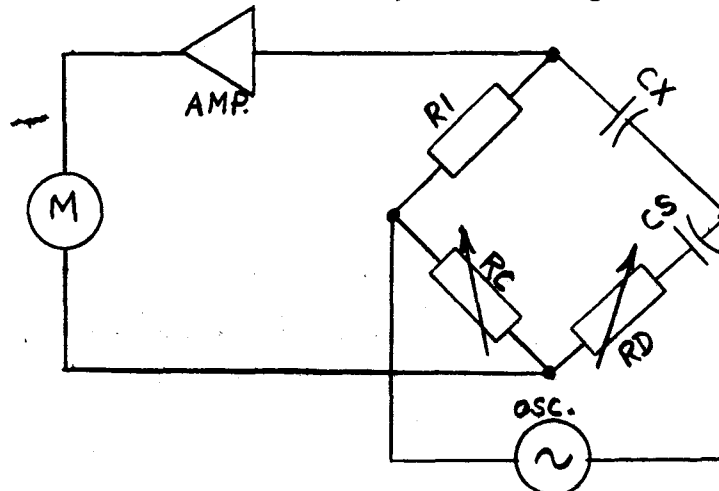
Capacitance and dissipation factor values for polycarbonate and paper capacitors were determined for a temperature range from -55°C to +85°C and frequency range from 0.4 to 10 kilocycles with sinusoidal waveforms.

Tests

Capacitance values were measured with an impedance bridge constructed for these tests. This bridge was constructed with components and interconnections to facilitate a minimum of stray and unknown capacitances and inductances over the frequency range. An elementary diagram of this type bridge is shown in Figure 2. Capacitance values measured with this bridge compared favorably with values obtained with a General Radio Model 716-C and Sprague Model 1W2 capacitance bridges.

Capacitor dissipation factors measured with the impedance bridge were considered comparative data that required adjustment with data obtained from calorimeter heat loss measurements. Adjustment of these dissipation factor data was necessary because unknown and stray capacitances of the bridge were still appreciable in the frequency range of interest.

Elementary Diagram of Impedance Bridge



$R1 = 99.7 \text{ OHMS}$; $CS = .01 \text{ MFD.}$, GEN. RADIO STD. 14C9L

CX - Capacitor under test

RC - Adjustable resistance (switch, fixed resistors and a potentiometer)

RD - Adjustable resistance (switch, fixed resistor and a potentiometer)

AMP. - Battery operated, single stage, transistor amplifier

M - Meter, Harmonic Wave Analyzer - used as null detector

$$\text{Dissipation Factor} = \frac{R_{cx}}{X_{cx}} = \frac{RD}{X_{cs}} = RD(CS)\omega$$

Where R_{cx} is the effective resistance of capacitor under test.

$$\text{Capacitance: } \frac{R1}{RC} = \frac{X_{cx}}{X_{cs}} \quad CX = \frac{CS(RC)}{R1}$$

Figure 2

Use of the calorimeter was made in measuring the rate of heat being generated from a capacitor immersed in a fluid and observing the rate of temperature rise. Calibration of the calorimeter is accomplished by mounting a known value of resistance to the capacitor surface within the calorimeter and measure the direct current flowing in the resistor while observing the rate of temperature rise of the calorimeter fluid. Caution was exercised to measure the rate of temperature rise after the thermal inertia had been overcome.

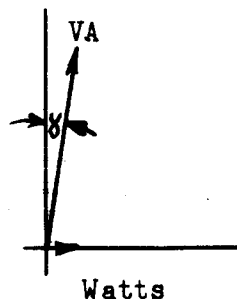
Calculation of the heat input to the calorimeter may be obtained from calibration with known heat input rate:

$$I^2R = \text{Watts} = ^\circ\text{C}/\text{minute}$$

After calibrating the calorimeter, the capacitor is energized from a variable frequency power supply with sinusoidal voltage. Capacitor dissipation factor (D.F.) is obtained from measurements of the RMS voltage across the capacitor and rate of temperature rise of the calorimeter fluid and by use of the following calculations:

$$\text{D.F.} = \frac{\text{Watts} \left(\frac{\Delta ^\circ\text{C}}{\Delta t} / \text{calibration} \frac{\Delta ^\circ\text{C}}{\Delta t} \right)}{VA \frac{E^2 \omega C}{E^2 \omega C}}$$

Shown diagrammatically



E = Capacitor rms voltage

C = Capacitance

Note: Since the angle alpha (α) is generally small, the dissipation factor is essentially equal to the capacitor power factor.

Care was exercised to minimize the calorimeter heat loss rate by maintaining the calorimeter fluid temperature within $\pm 2^\circ\text{C}$ of the calorimeter external ambient ($24 - 26^\circ\text{C}$ within the enclosure). Maintaining the calorimeter fluid temperature relation to the ambient was accomplished by replacement of the fluid between tests.

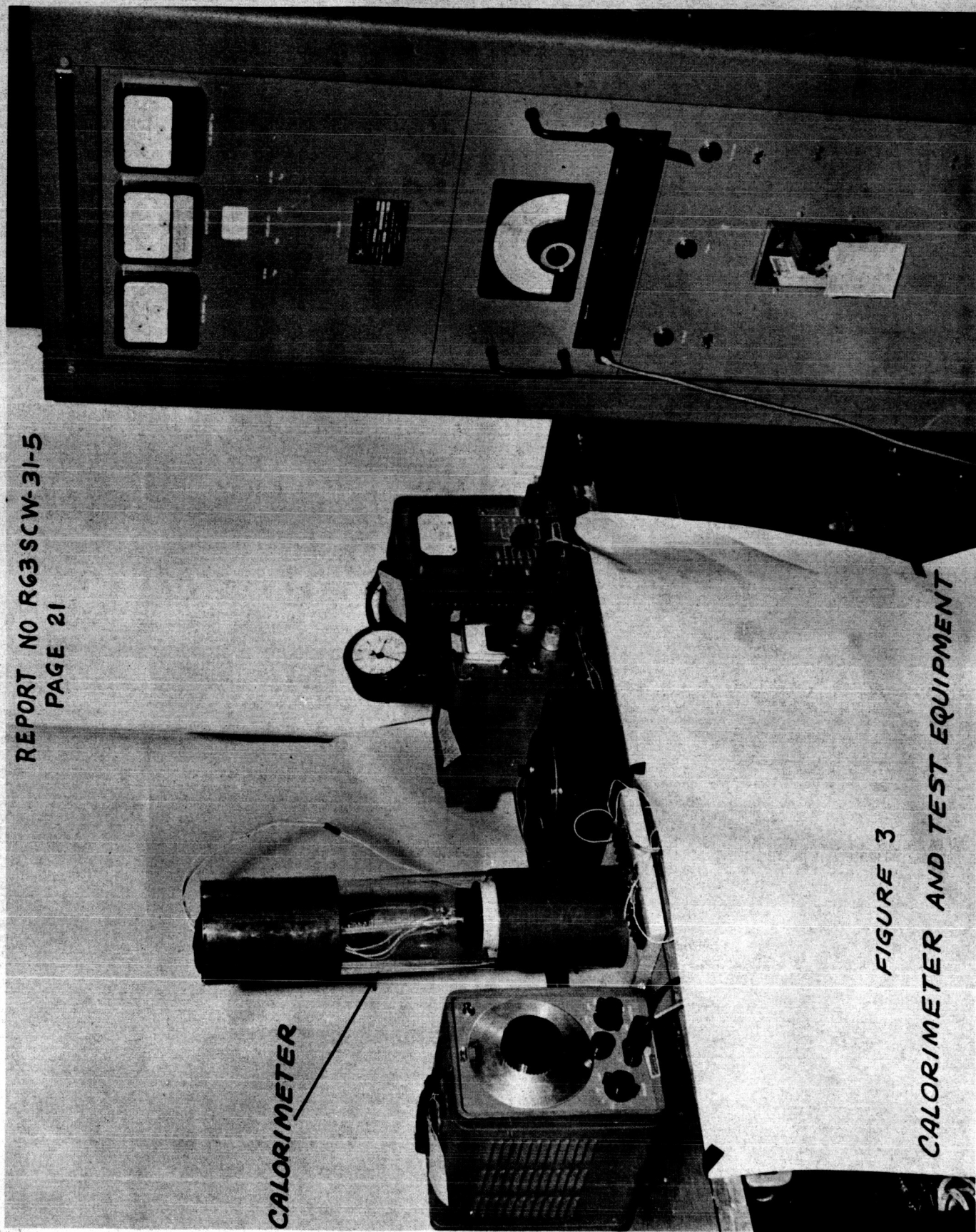
The calorimeter fluid quantity was kept constant during the tests by utilizing weight measurements when replenishing the fluid.

A picture of the test equipment used is shown in Figure 3. Figure 4 shows the mounting of a capacitor, calibrating resistors and thermometer to the top of a commercially available vacuum bottle, which was used as a calorimeter. The calorimeter shown in Figure 3 is in an enclosure to prevent room air currents from striking the external surfaces of the calorimeter that could alter the heat loss rate from the calorimeter.

Testing of the tantalum electrolytic capacitors was limited to bridge measurements in ambient temperatures from -55°C to $+85^{\circ}\text{C}$ and frequencies from 120 to 1200 cps.

CALORIMETER

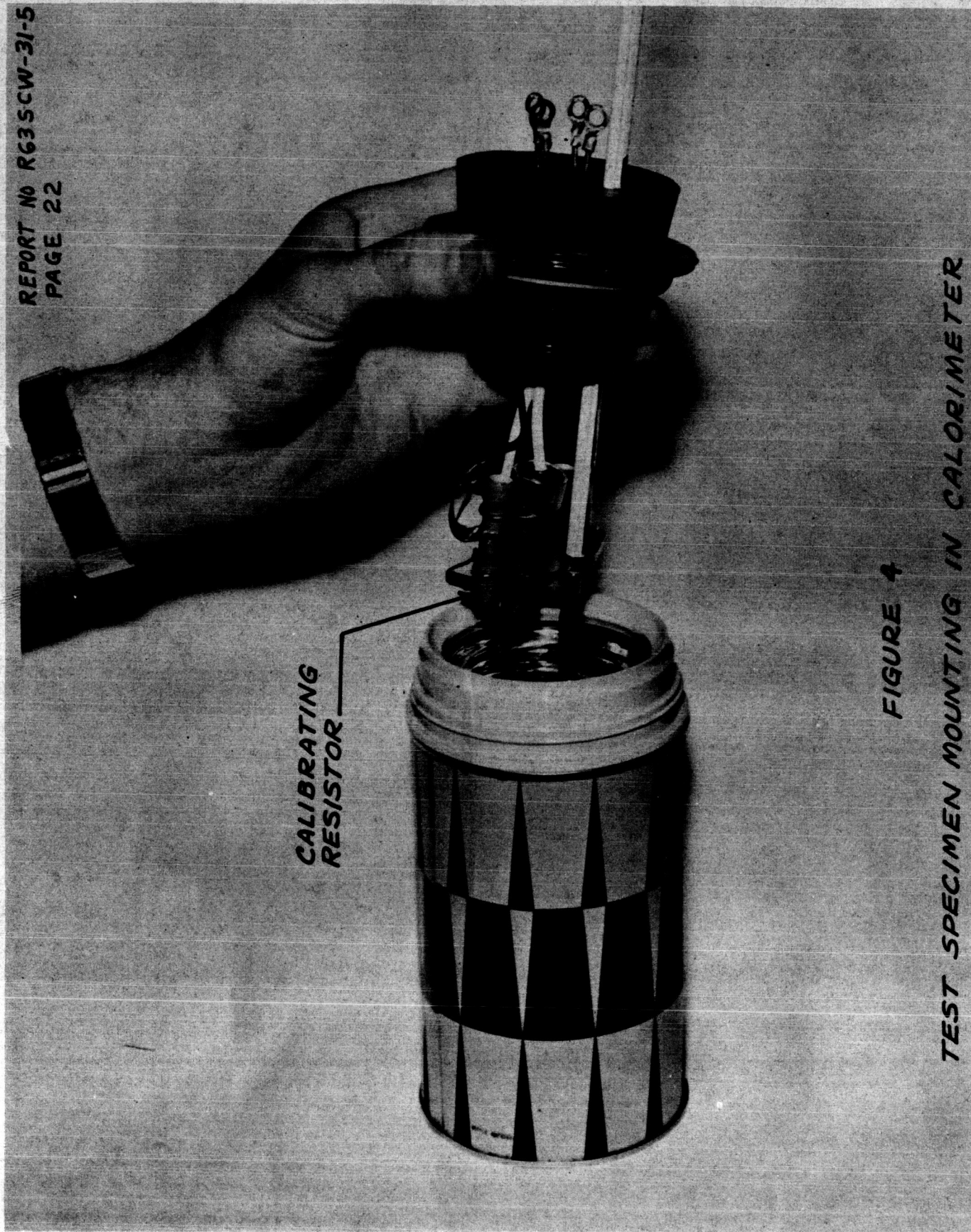
FIGURE 3
CALORIMETER AND TEST EQUIPMENT



CALIBRATING
RESISTOR

FIGURE 4

TEST SPECIMEN MOUNTING IN CALORIMETER



Results

Capacitance and dissipation factor test data in 25°C ambient for twenty (20) metallized paper, forty-five (45) metallized polycarbonate and twenty-four (24) polycarbonate/foil capacitors are contained in Tables B1 through B3 in Appendix B of this report.

The average of the percent capacitance change versus frequency data from Tables B1 through B3 is shown in Figure 5. At 10 kilocycles the average capacitance variation of metallized paper is 1.68 percent compared to a 2.95 percent average for metallized polycarbonate and a 3.85 percent average for polycarbonate/foil capacitors. The lower capacitance variation with frequency of metallized paper capacitors in 25°C ambient is attributed to the longer established quality control of materials and techniques in comparison to the relatively new polycarbonate capacitors.

The average of the percent dissipation factor versus frequency data from Tables B1 through B3 is shown in Figure 6. In general, the average of the dissipation factor for polycarbonate/foil capacitors is one-half the value of metallized polycarbonate and one quarter the value of metallized paper capacitors.

Capacitance and dissipation factor test data versus temperature and frequency in Tables B4 through B6 are shown in Figures 7 and 8, respectively. Capacitance change with temperature and frequency shown in Figure 7 for metallized paper capacitors is 12 percent, for polycarbonate/foil, it is 5.5 percent and for metallized polycarbonate, it is 3 percent.

Dissipation factor variation with temperature and frequency varies from 0.03 to 0.46 percent for polycarbonate/foil, 0.55 to 1.23 percent for metallized polycarbonate and 0.16 to 1.93 percent for metallized paper capacitors as shown in Figure 8.

Some test data as indicated are excluded from the presentation in Figure 8 because these data exhibited excessive variation and were not considered representative.

Dissipation factor test data were obtained from two (2) metallized paper, four (4) polycarbonate/foil and three (3) metallized polycarbonate capacitors over an extended frequency range in 25°C ambient. These data, obtained with calorimeter measurements are shown in Figure 9. Generally, the dissipation factor for all three (3) types of capacitors increase 100 percent between 10 and 50 kilocycles.

Average Percent Capacitance Change Versus Frequency in 25°C Ambient

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Key:

- A - Data curve for a total of 24 polycarbonate/foil capacitors from 3 manufacturers and include 1, 2, 3 and 5 MFD. Ratings
- B - Data curve for a total of 45 metallized polycarbonate capacitors from 5 manufacturers and include 1, 2, 2.5 and 3 MFD ratings.
- C - Data curve for a total of 20 metallized paper capacitors from 2 manufacturers and include 2 and 3 MFD ratings.

Test Data Referenced to 400 CPS values

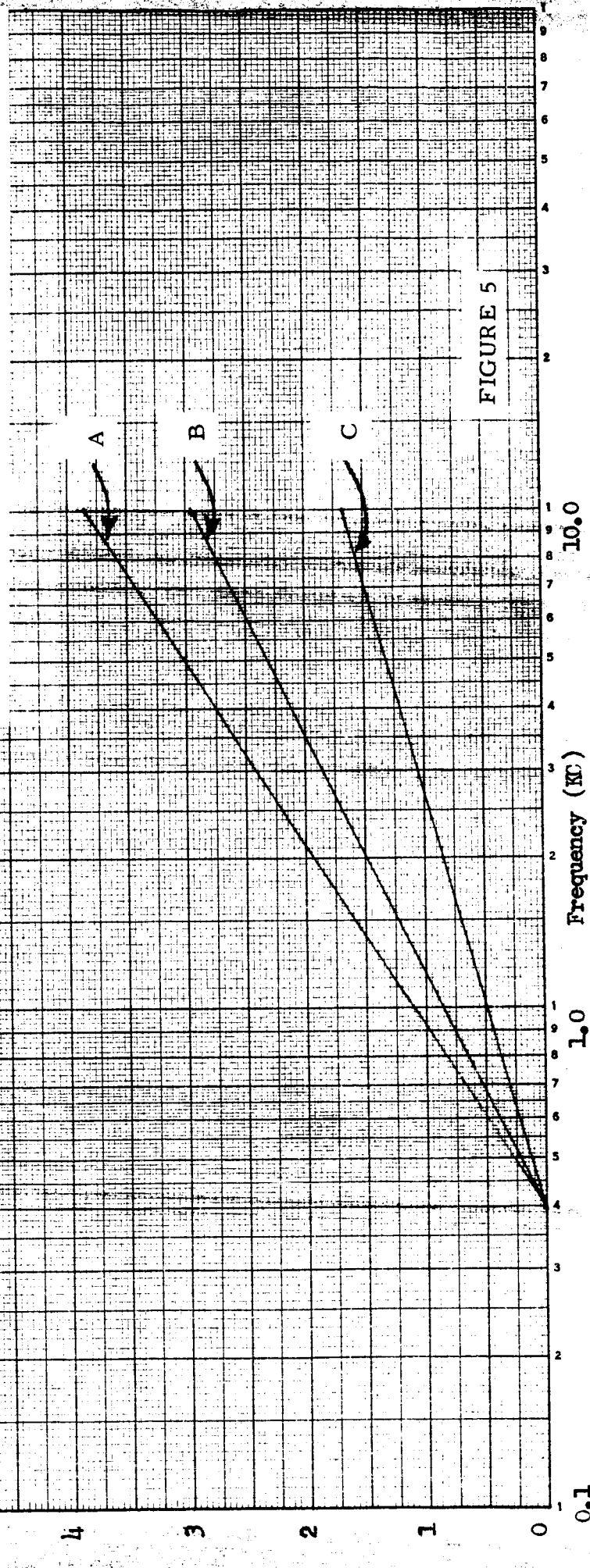


FIGURE 5

Average Percent Dissipation Factor Versus Frequency in 25°C Ambient

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Key

A - Data curves for a total of 20 metallized paper capacitors from 2 mfrs and include 2 and 3 MFD ratings.

B - Data curves for a total of 39 metallized polycarbonate capacitors from 5 mfrs. and include 1, 2, and 3 MFD ratings. Data from Capacitor Nos. 2E, 3A to 3E in Table B1 are excluded.

C - Data curves for a total of 24 polycarbonate/foil capacitors from 3 mfrs. and include 1, 2, 3, and 5 MFD ratings.

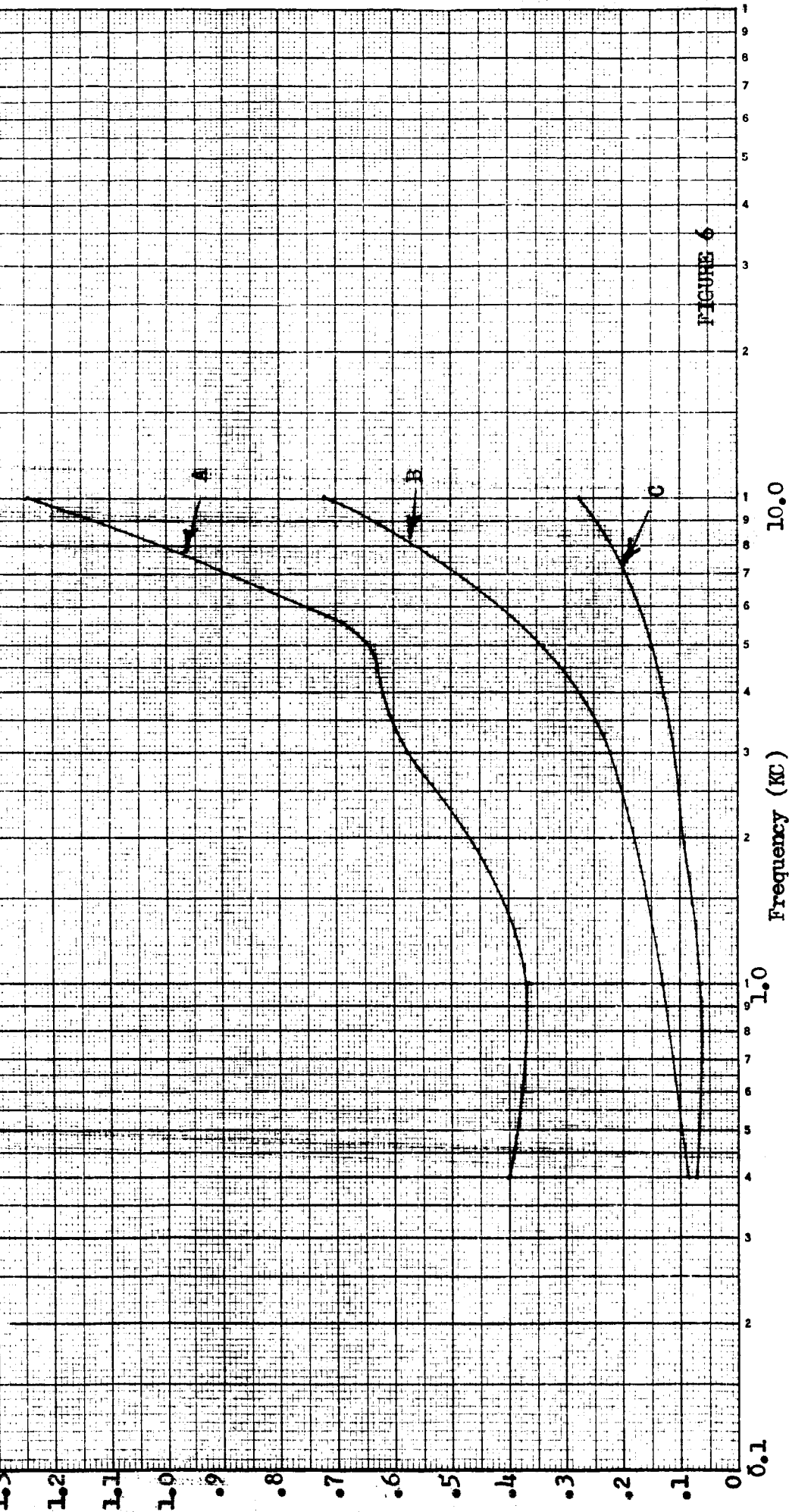
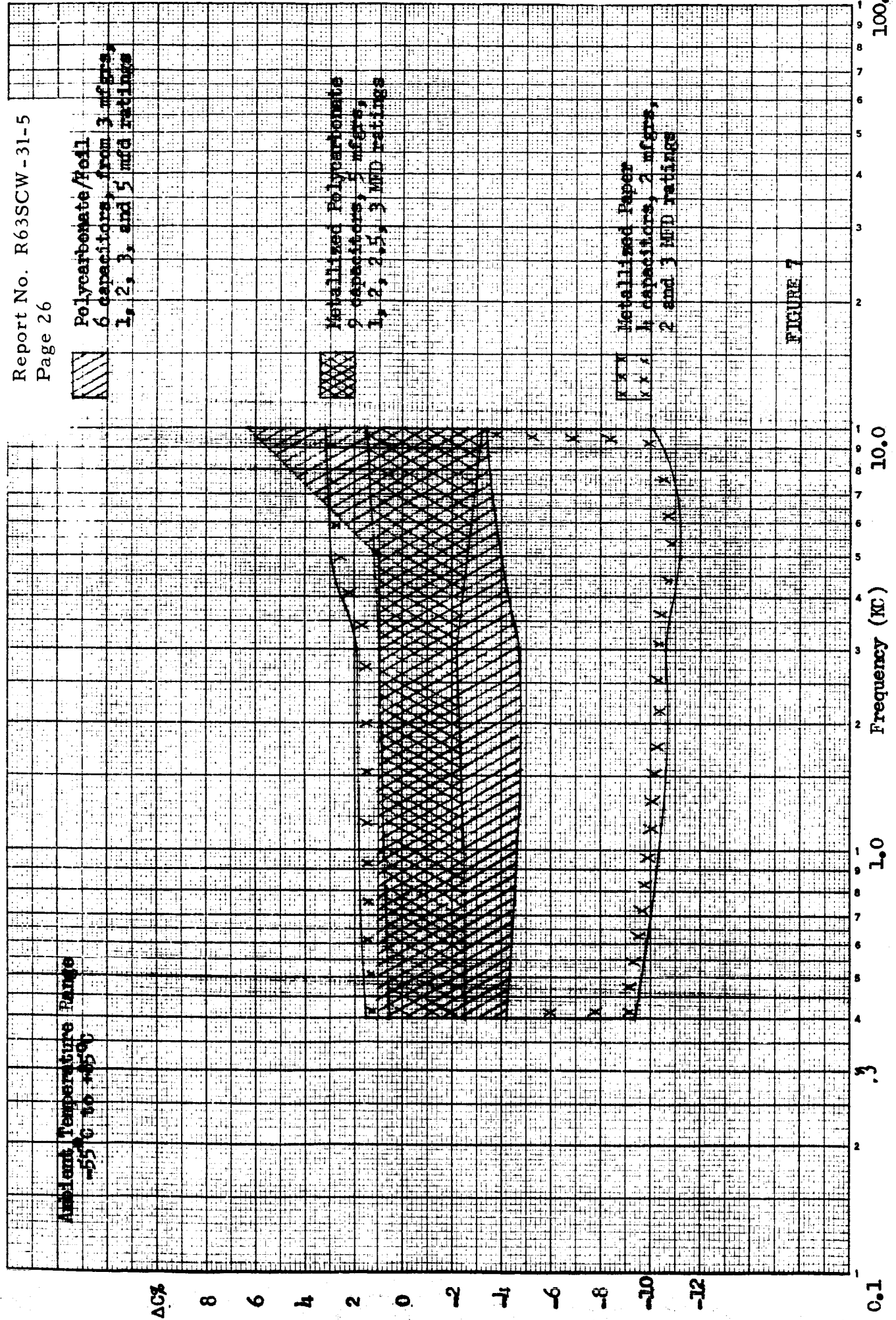


FIGURE 6

Percent Capacitance Change Versus Frequency and Temperature

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Percent Dissipation Factor Versus Frequency and Temperature

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Ambient Temperature Range
= 55°C to + 85°C

 Metallized polycarbonate
6 capacitors, 5 mfd.
1, 2 and 3 mfd. Ratings
Data for capacitor
Nos. 25, 30, 15B from
Table B4 excluded

 Polycarbonate/foil
5 capacitors, 3 mfd.
1, 3 and 5 mfd. Ratings
Data for capacitor No.
10A from Table B5 excluded


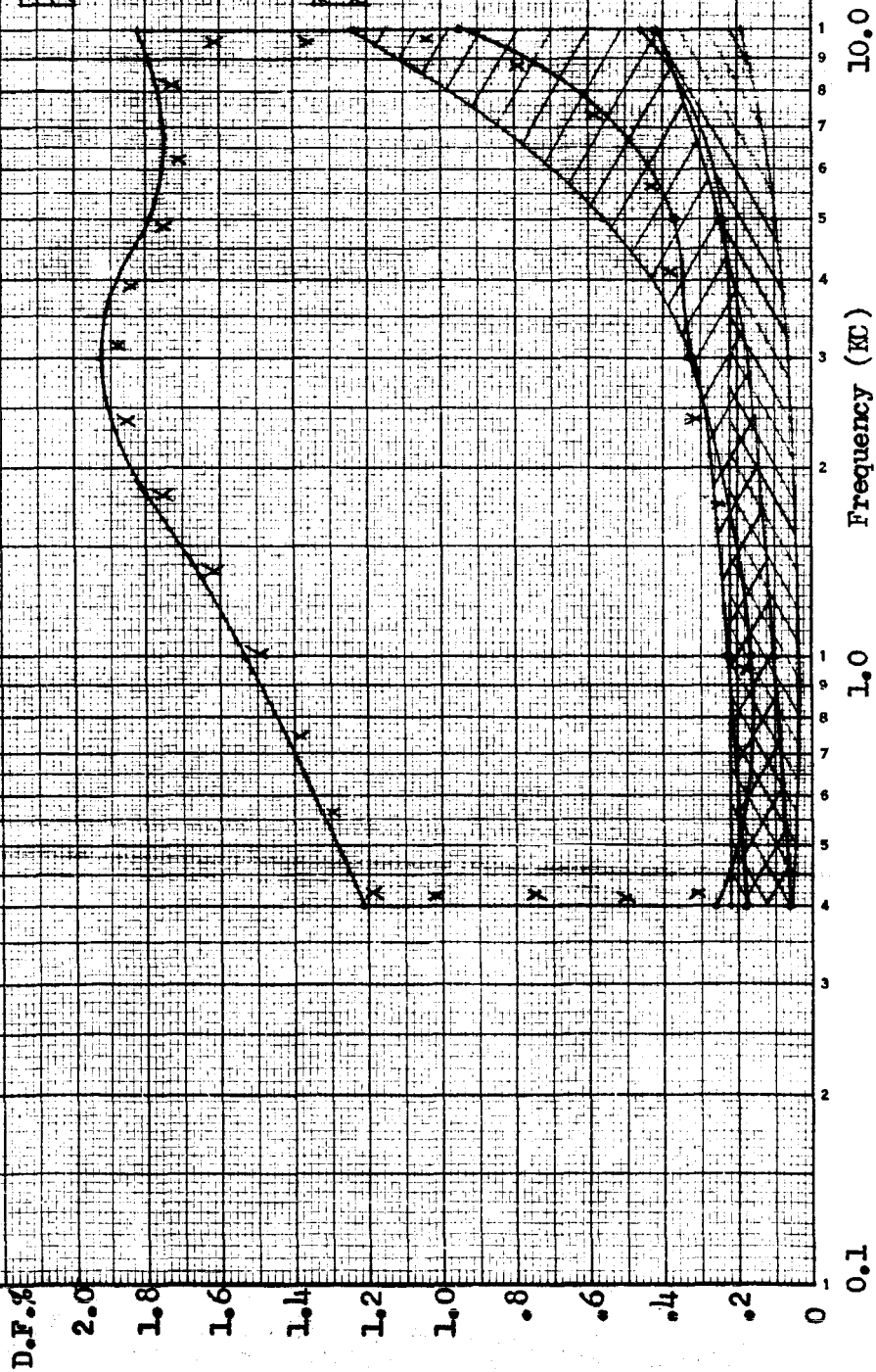
 Metallized paper
3 capacitors, 2 mfd.
2 and 3 mfd. Ratings
Data for capacitor No.
8A from Table B6 excluded

FIGURE 8



Percent Dissipation Factor Vs. Extended Frequency in 25°C Ambient

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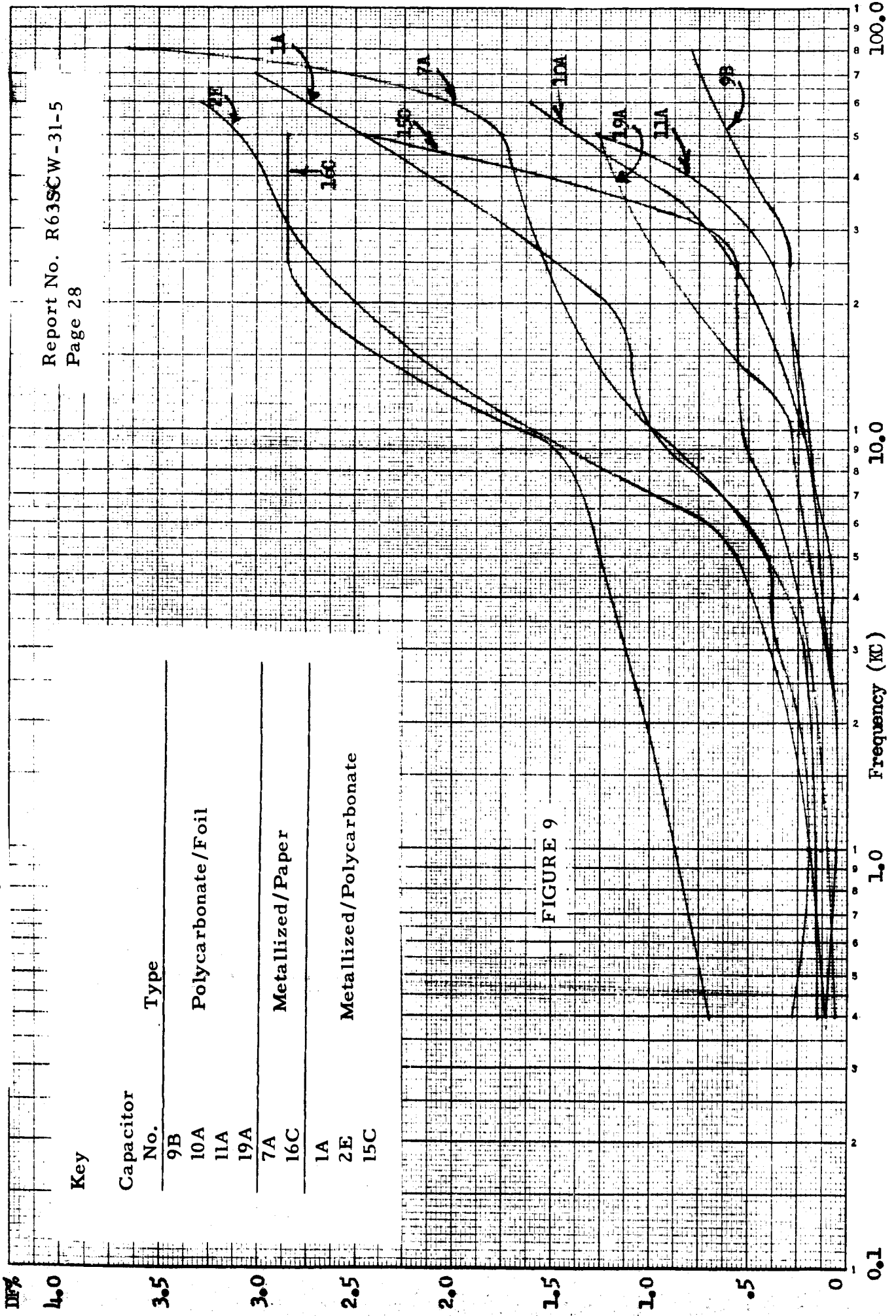


FIGURE 9

Commutating capacitors are often subjected to ripple frequencies in this range in static inverter. Such ripple frequencies can be caused by minor resonances between inductive and capacitive components.

Capacitance and dissipation factor test data for sintered and foil tantalytic capacitors versus frequency and temperature are shown in Table B7.

The decreasing capacitance characteristic with decreasing temperature and increasing frequency is a maximum of 12.65 percent from -25°C to $+85^{\circ}\text{C}$ and 120 to 1200 cps as shown in Table B7. However, capacitance change variations of 59.6 percent and 29.8 percent maximum for sintered and foil capacitors, respectively, over a temperature range for -55°C to $+85^{\circ}\text{C}$ and 120 to 1200 cps were measured. Similarly, the dissipation factor increases with decreasing temperature and frequency, within the frequency range of the tests as shown in Figure 10. These data and physical data comparisons shown in section 2.1 of this report are primarily for reference purposes.

3.2 Commutating Capacitor Test and Results

A method of correlating capacitor losses, while operating in commutating circuits, to capacitor losses measured with more conventional test equipment and sinusoidal voltage was sought in this study.

Test

A 2.5 microfarad, 500 VDC metallized polycarbonate capacitor was mounted in a calorimeter and its dissipation factor determined utilizing sinusoidal voltages over a frequency range from 400 cycles/second to 50 kilocycles in a 25°C ambient.

While mounted in the calorimeter, the capacitor was then connected to a static inverter and operated as a commutation capacitor. The capacitor heat loss was calculated from the calorimeter heat measurements. Calibrated oscilloscope pictures of the capacitor voltage and current waveforms were obtained during this test for use in analysis of the capacitor losses.

Average Dissipation Factor for Tantalum Capacitors

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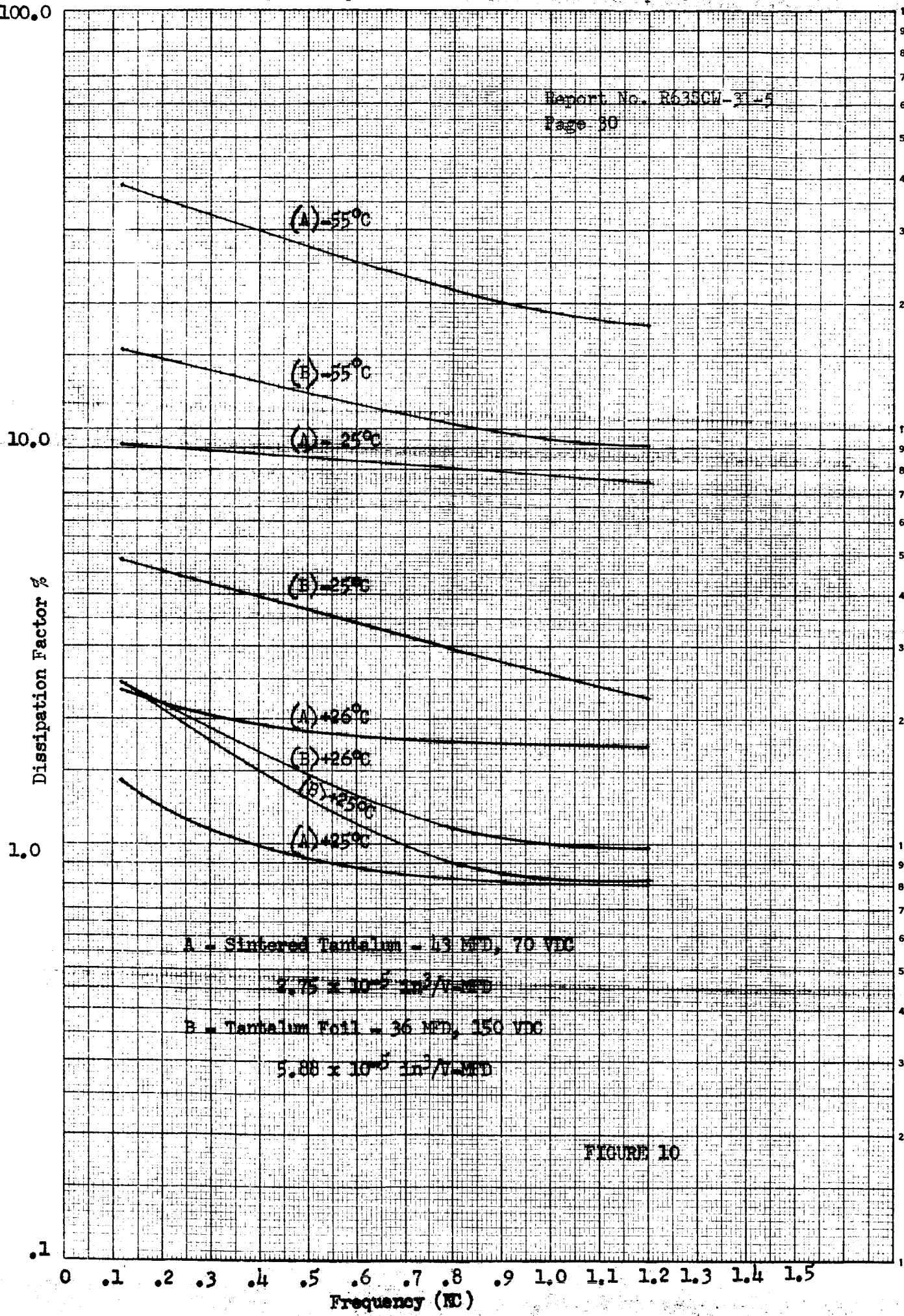


FIGURE 10

Results

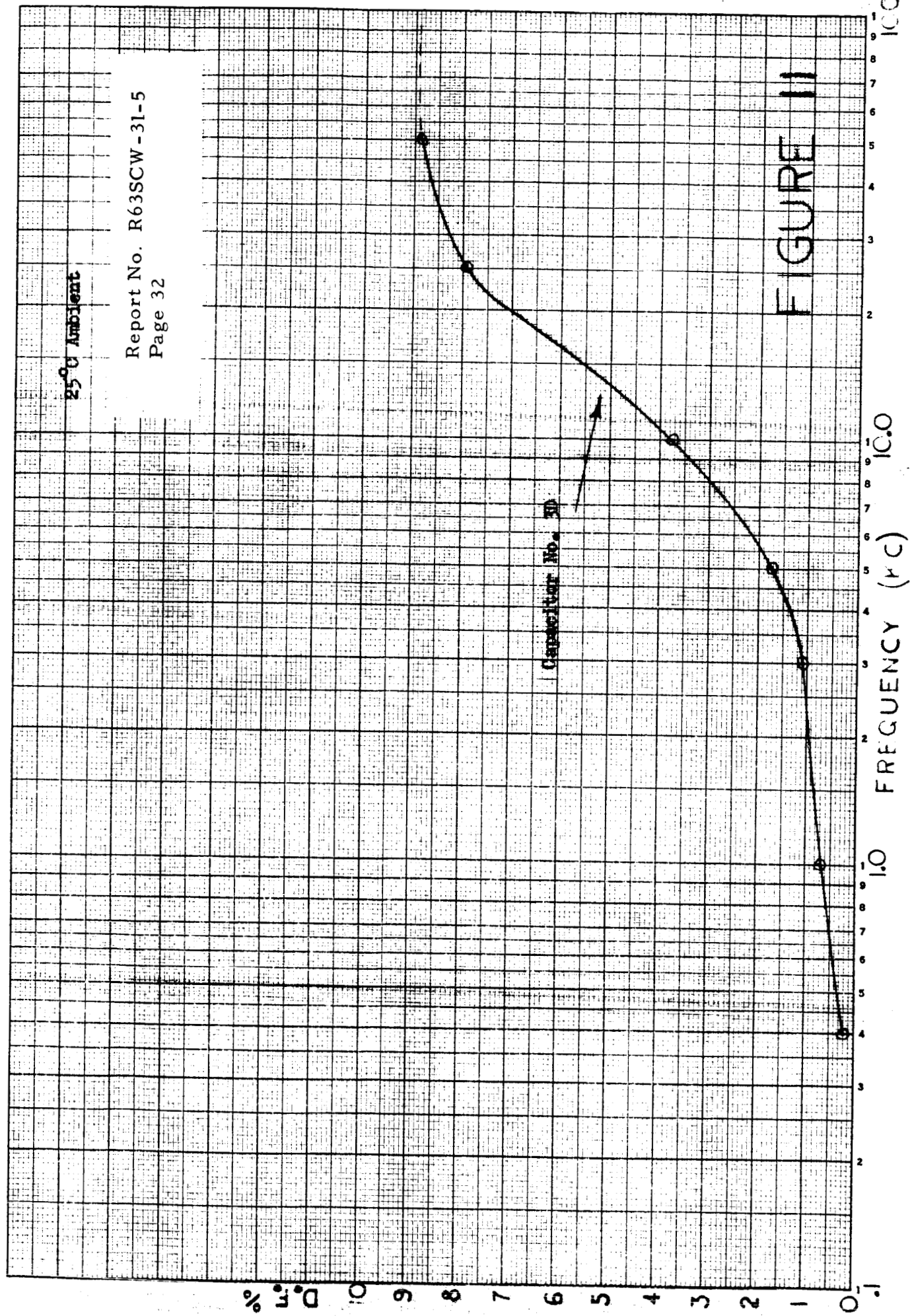
The dissipation factor of the commutating capacitor versus frequency characteristic is shown in Figure 11. It should be noted that the dissipation factor for this capacitor is much greater than for the polycarbonate capacitors shown in Figure 9 but the results of the test are valid.

Actual commutating capacitor losses while operating in the inverter circuit were 0.91 watts. Capacitor voltage and current waveforms, during this test, are shown in Figure 12. The encircled portions of the waveforms in Figure 12 were subjected to analysis to determine the RMS voltage and currents. A detailed wave analysis was considered necessary because the waveforms contained a significant amount of ripple.

Evaluating the rms volt-amperes of the encircled portions of the commutating capacitor waveform was accomplished as follows:

- 1) Voltage and current values from expanded portions of the waveforms as shown in Figures 13 and 14 were scaled at 5 microsecond ordinates as illustrated in Figure 13. These scaled values were squared and replotted as squared voltage and current curves.
- 2) A polar planimeter was then used to measure the areas under these new curves (i.e. volt²-seconds or ampere²-seconds).
- 3) The areas under the squared voltage and current waves were divided by the 400 cycle/second time base and the square root of the resultant was taken to obtain RMS values of the voltage and current.
- 4) An assumption was made that the commutating current pulse conformed to a quarter sine wave function during an interval of 47.5 microseconds and had a peak value of 10.2 amperes. It was also assumed that the voltage function during this time interval conformed to a cosine function. From these assumptions, RMS voltage and current values were calculated for smooth waveforms as shown in Figure 15.
- 5) The RMS values obtained in 4) above were subtracted from those obtained in 3) above. The difference between these RMS voltage and current values was attributed to the ripple frequency.

Dissipation Factor for 2.5 μ F Metallized Polycarbonate Capacitor



COMMUTATING CAPACITOR WAVEFORMS

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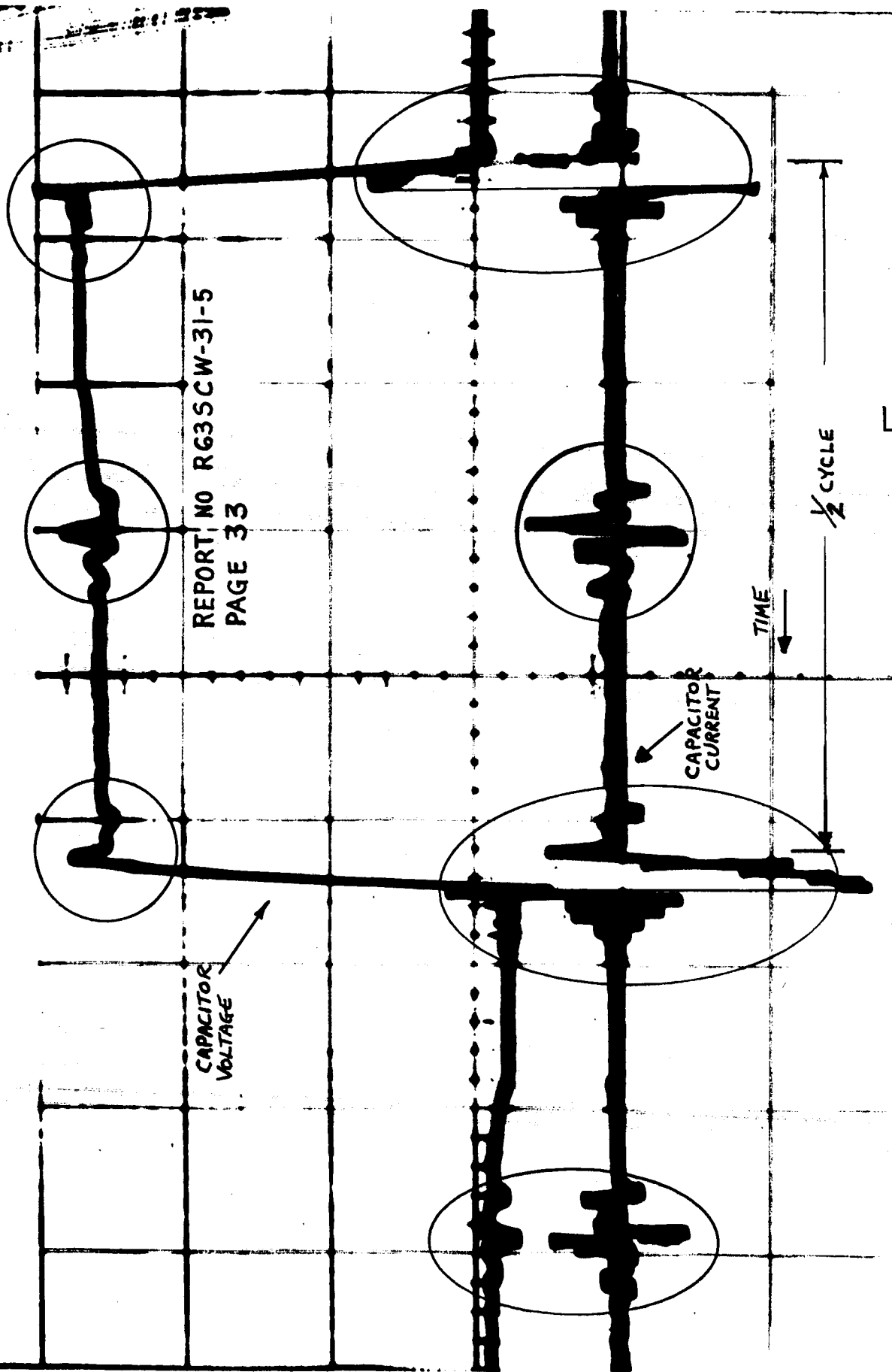


FIGURE 12

COMMUTATING CAPACITOR WAVEFORMS

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I^2 1250 A² μ sec.
SCALE

V^2 250,000 V² μ sec.
SCALE

I SCALE I = 5 AMPS/LARGE DIV. 0 AMPS
V SCALE V = 50V/LARGE DIV. 0 VOLTS

25 μ sec.

FIGURE 13

COMMUTATING CAPACITOR WAVEFORMS

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CAPACITOR VOLTAGE (50 VOLTS/LARGE DIV)

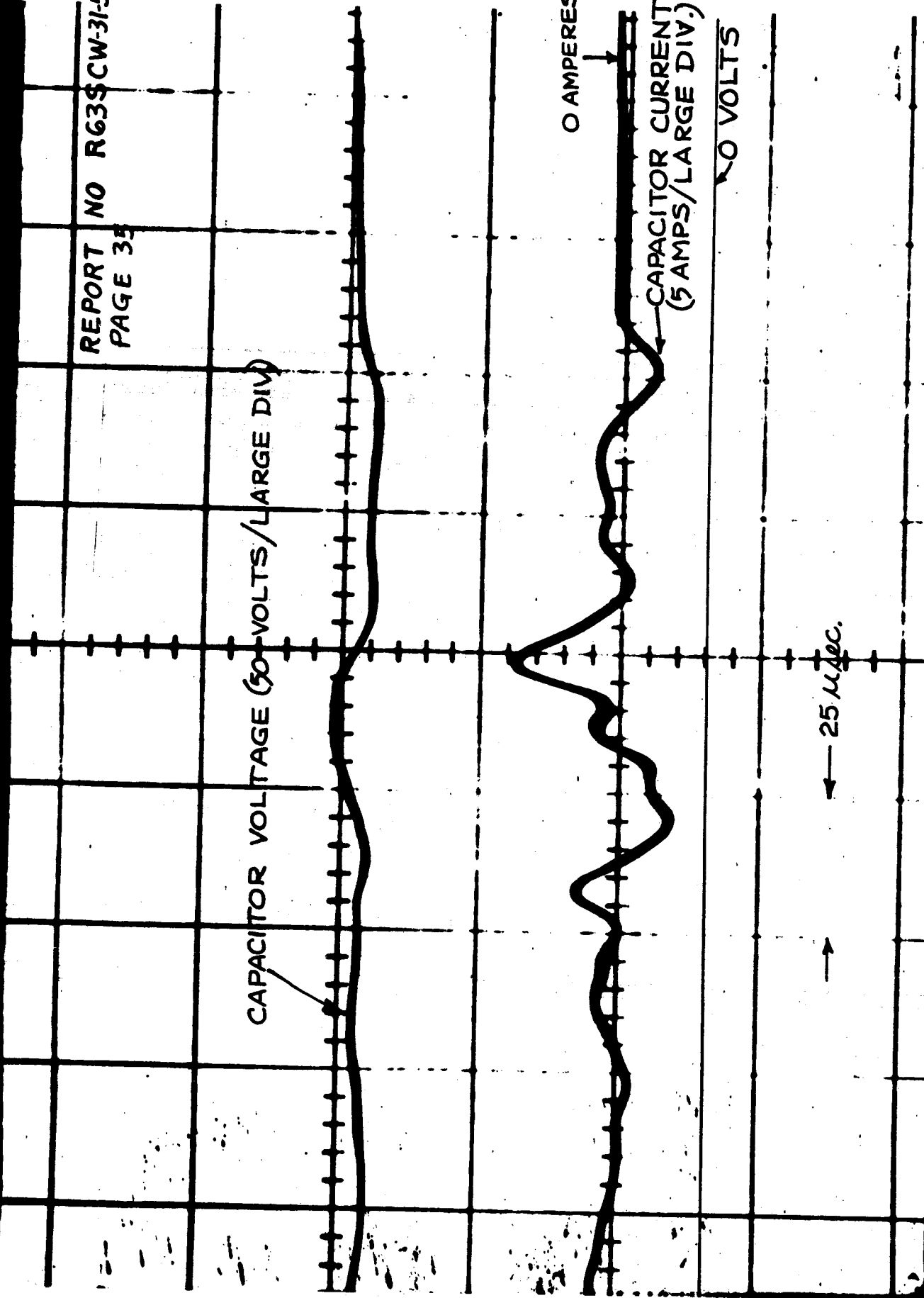
0 AMPERES

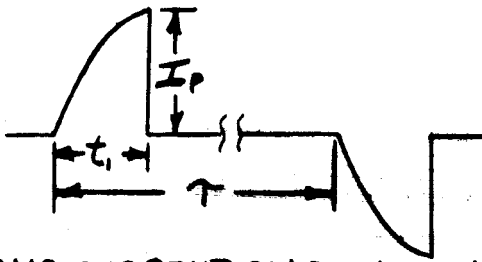
CAPACITOR CURRENT
(5 AMPS/LARGE DIV.)

0 VOLTS

25 μ sec.

FIGURE 14



RMS CURRENT AND VOLTAGE FOR COMMUTATION PULSE

RMS CURRENT CALCULATION

$$t_i = 47.5 \mu\text{SEC} ; T = 1256 \mu\text{SEC} ; f_0 = 400 \text{ CPS} ; f_m = 5.28 \text{ Kc}$$

$$\omega_0 = 2\pi f_0 ;$$

$$\omega_m = 2\pi f_m$$

$$I_{rms}^2 = \frac{1}{T} \int_0^{t_i} i^2 dt$$

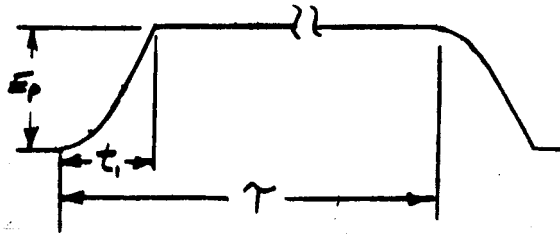
$$i = I_p \sin \omega_m t$$

$$\begin{aligned} I_{rms}^2 &= \frac{I_p^2 \omega_0}{\pi} \int_0^{\frac{\pi}{2\omega_m}} (\sin^2 \omega_m t) dt \\ &= \frac{I_p^2 \omega_0}{\pi} \left[\frac{t}{2} - \frac{t}{4\omega_m} \sin 2\omega_m t \right]_0^{\frac{\pi}{2\omega_m}} \\ &= \frac{I_p^2 \omega_0}{4\omega_m} \end{aligned}$$

$$I_{rms} = 0.138 I_p$$

$$I_p = 10.2$$

$$I_{rms} = 0.138(10.2) = 1.41$$



RMS VOLTAGE CALCULATION

$$E_{rms}^2 = \frac{1}{T} \int_0^{t_i} e^2 dt$$

$$e = E_p (1 - \cos \omega_m t)$$

$$\begin{aligned} E_{rms}^2 &= \frac{E_p^2 \omega_0}{\pi} \int_0^{\frac{\pi}{2\omega_m}} (1 - 2\cos \omega_m t + \cos^2 \omega_m t) dt \\ &= \frac{E_p^2 \omega_0}{\pi} \left[t - \frac{2}{\omega_m} \sin \omega_m t + \frac{t}{2} + \frac{1}{4\omega_m} \sin 2\omega_m t \right]_0^{\frac{\pi}{2\omega_m}} \\ &= E_p^2 \frac{\omega_0}{\omega_m} (0.75 - 0.636) = 0.114 \frac{E_p^2 \omega_0}{\omega_m} \end{aligned}$$

$$E_{rms} = 0.093 E_p$$

$$E_p = 127$$

$$E_{rms} = 0.093(127) = 11.8$$

FIGURE 15

From Figure 13, the commutation current pulse duration is 47.5 microseconds. The shape of this pulse approximates a quarter sine wave with a frequency of

$$f = \frac{1}{4t} = \frac{1}{4(47.5) \times 10^{-6} \text{sec}} = 5.28 \text{ kilocycles}$$

The shape of the voltage waveform during the commutation current pulse interval is cosinusoidal. The RMS volt-ampere for these wave functions during the commutation interval is derived in Figure 15 and numerically is 16.6 volt-amperes.

The sums of the squared volt-second and ampere-second values from the waveform, a portion of which is shown in Figure 13, are:

$$(1) \frac{4,505,217 \text{ Volt}^2\text{-usec}}{2500 \text{ usec}} = 1820 \text{ volt}^2$$

$$(2) \frac{6646 \text{ amp}^2\text{-usec}}{2500 \text{ usec}} = 2.655 \text{ amp}^2$$

$$V_{rms} = \sqrt{1820} = 42.6 \text{ volts}$$

$$I_{rms} = \sqrt{2.655} = 1.63 \text{ amps}$$

The capacitor loss from the commutation pulse with an equivalent 5.28 kilocycle frequency is calculated using a dissipation factor of 1.85 percent for 5.28 kilocycles in Figure 11, 1.41 amperes rms and 11.8 volts rms in Figure 15:

$$VI \text{ (D.F.)} = (11.8) (1.41) (.0185) = 0.307 \text{ watts}$$

Subtraction of the rms volt-amperes of the commutation pulse from the rms voltage and current totals yield the rms volt amperes of the ripple:

$$\begin{aligned} 42.6 &= 11.8 = 30.8 \text{ Volts rms} \\ 1.63 &= 1.41 = 0.22 \text{ amps rms} \end{aligned}$$

The product of the RMS voltage and current of the ripple and the capacitor dissipation factor determined with sinusoidal voltages at the ripple frequency yields:

$$(1) \text{ Dissipation Factor from Figure 11 for 80 kilocycles} \cong 8.9\%$$

$$(2) VI \text{ (D.F.)} = (30.8) (0.22) (.089) = .603 \text{ watts}$$

The sum of the watts attributed to the ripple and commutating pulse is:

0.307 watts (commutation pulse)
0.603 watts (ripple)
0.91 watts

The measured commutation capacitor loss in the calorimeter was 0.91 watts and a favorable agreement was achieved with the analysis above.

3.3 Life Test and Results

Description

A total of fifty (50) capacitors were subjected to life test of 1000 hours in 85°C ambient while energized with 420 cps voltage. This test was conducted to determine if the capacitors could withstand AC peak voltages equivalent to the DC voltage ratings with the exception of capacitors having DC voltage ratings above corona starting voltage region of 325-340 volts. Corona starting voltage is the voltage level at which ionizing of air or gases entrapped between layers of the dielectric roll takes place. These ionized gas pockets create hot spots that can progressively deteriorate the dielectric. Fifty (50) capacitors (33 metallized polycarbonate, 12 polycarbonate/foil and 5 metallized paper capacitors) were mounted on the inner walls of a sealed aluminum box, shown in Figure 16. The surface of the aluminum box was maintained at a temperature of 85 ± 3°C for the duration of the test. Figure 17 illustrates instrumentation and indicating lights in parallel with fuses that were in each capacitor circuit as illustrated in the elementary diagram in Figure 18.

Ratings of the fuses in series with the capacitors were selected to be approximately three (3) times the rated capacitor current. Detection of a shorted capacitor during the test was by observation of the indicator lights that were on, indicating the fuses that had open circuited.

Capacitors that may have failed in an open circuit mode only would have been detected when capacitance and dissipation factor data were taken at the conclusion of the test.

Capacitors with 300 and 400 VDC ratings were energized with 325 volts peak. Capacitors with 200 VDC ratings were energized with 212 volts peak. The 135 and 157 volt DC capacitor ratings were energized with 162 volts peak.

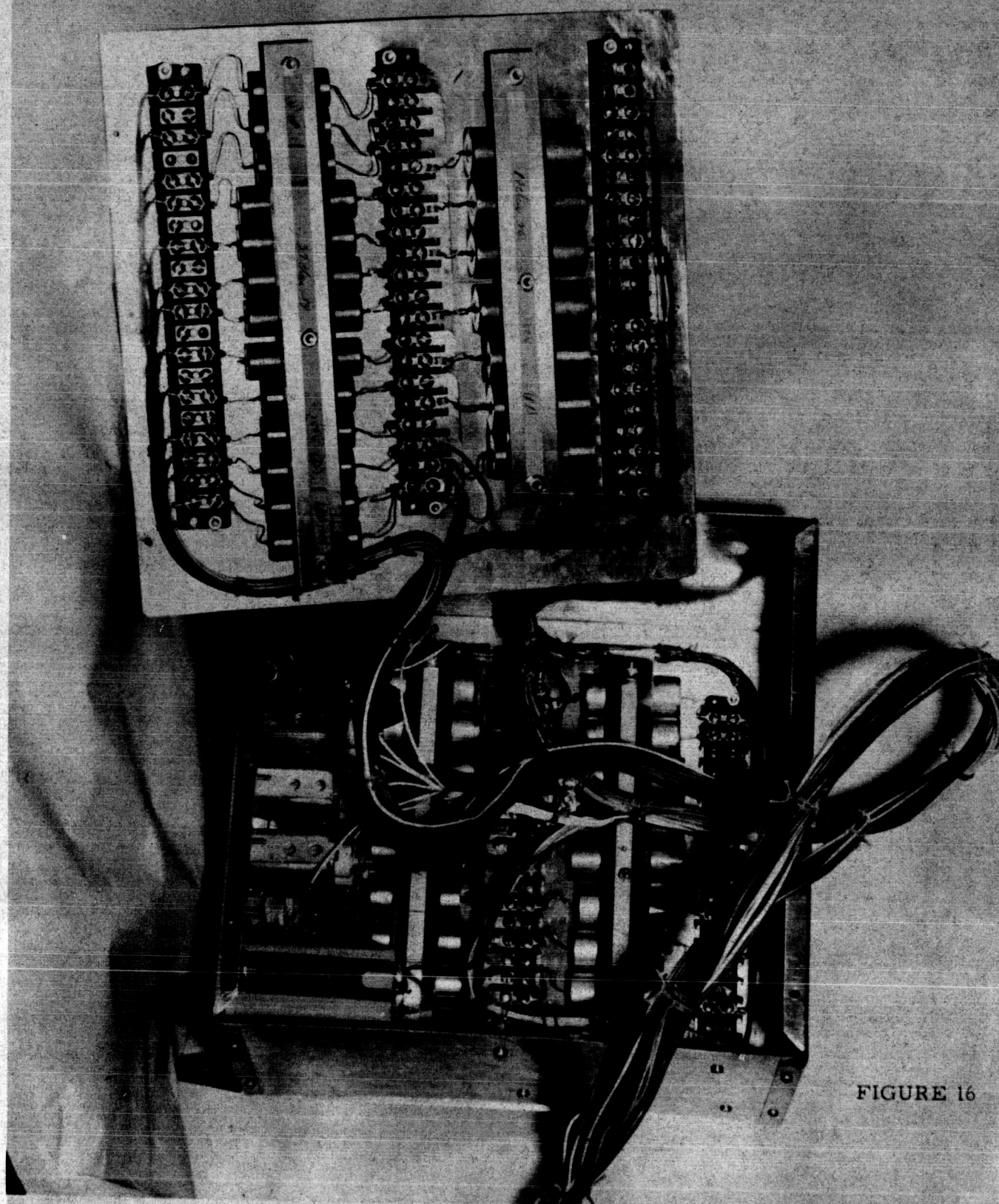


FIGURE 16

MOUNTING OF LIFE TEST CAPACITORS

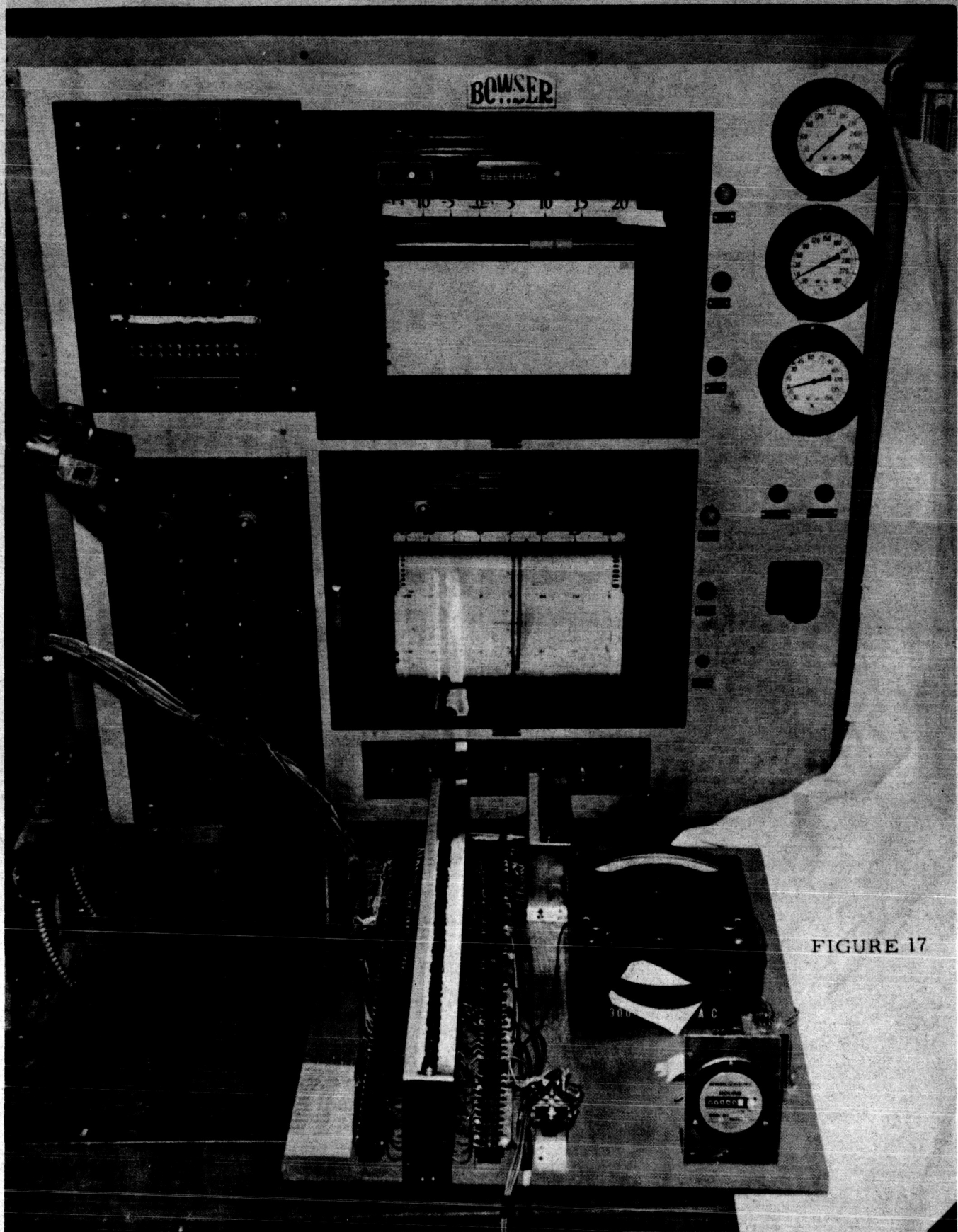
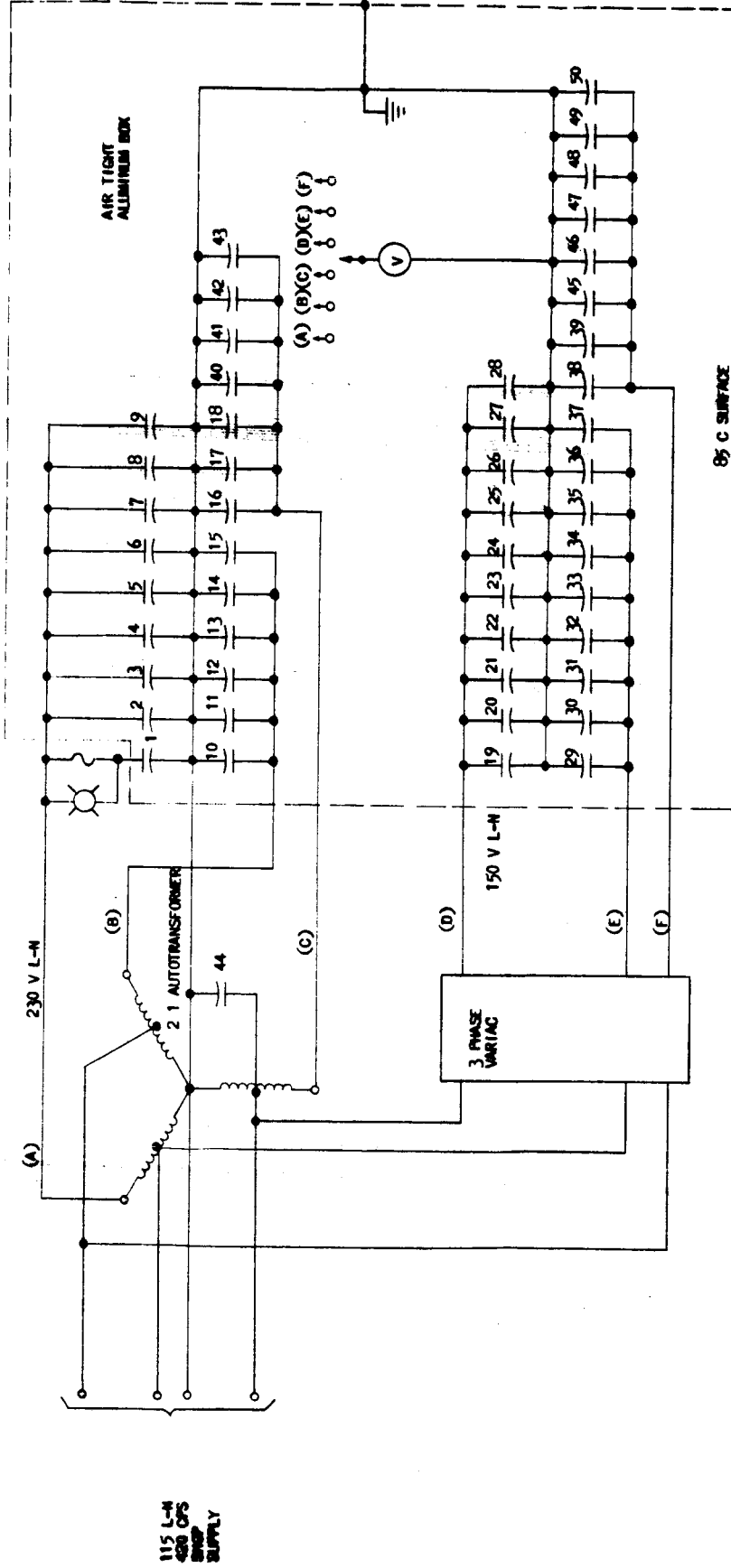


FIGURE 17

LIFE TEST MONITORING EQUIPMENT

THERMOCOUPLE
FOR OVEN CONTROL



NOTES
1. EACH CAPACITOR FUSED AS SHOWN BY CAPACITOR 1.
LIGHTS AND FUSES OUTSIDE OVEN.

CAPACITOR TYPES

1-2	MP	2 UF	400 VDC
3-5	PCF	1 UF	400 VDC
6-10	MPC	2 UF	400 VDC
11-13	MPC	2 UF	400 VDC
14-16	MPC	2 UF	300 VDC
17-18	MPC	2.55 UF	400 VDC
19	MP	2 UF	200 VDC
20-23	PCF	2 UF	200 VDC
24-26	MPC	3 UF	200 VDC
27-29	MPC	3 UF	200 VDC
30-34	MPC	3 UF	200 VDC
35-39	MPC	3 UF	200 VDC
40-43	MPC	1 UF	400 VDC
44	PCF	5 UF	157 VDC
45	MP	2 UF	200 VDC
46-48	PCF	3 UF	135 VDC
49	MP	2 UF	200 VDC
50	PCF	3 UF	135 VDC

PCF - POLYCARBONATE FILM AND ALUMINUM FOIL CONSTRUCTION
MPC - METALLIZED POLYCARBONATE FILM CONSTRUCTION
MP - METALLIZED PAPER CONSTRUCTION

FIGURE 18

The 325 volt peak limitation was maintained to prevent damage to the capacitors from corona.

A strip chart temperature recorder shown in Figure 17 was used to continuously monitor the temperature of the aluminum box containing the capacitors. The 420 cps voltages were recorded twice during each normal working day during the test. An elapsed time indicator was energized from the 420 cps voltage source to indicate total test time.

Capacitance and dissipation factor data was measured before and after the 1000 hour 85°C ambient test to determine load-life characteristics. Survivors of the 1000 hour life test in 85°C ambient were placed in a 125°C ambient and the life test was continued for 370 hours.

Results

There were thirteen (13) capacitors out of fifty (50) that failed by short circuiting during the 85°C ambient test.

Capacitors 3,4,5,&11 in Figure 18 developed short circuits upon step application of the 230 volt RMS, 420 cps power. This step application of power resulted in two (2) 350 V RMS transients and three (3) 280 V RMS transients from resonant effects between the capacitors and the transformer inductance.

Capacitors 20, 21, 23 and 30 in Figure 18 developed short circuits upon being energized.

The following capacitors developed short circuit during the life test as tabulated:

<u>Capacitor No.</u>	<u>Hours to Failure</u>
13	234.7
32	362.7
12, 33	474.8
31	666.7

The capacitors that failed during this test were from one (1) capacitor manufacturer. The fifty (50) capacitors subjected to this life test were obtained from six (6) capacitor manufacturers.

Analysis of the capacitors, that failed, by the capacitor manufacturer revealed that the causes of failure were attributed to construction techniques that have been improved upon since these capacitors were manufactured.

Five (5) capacitors developed short circuits during the 370 hours test at 125°C ambient. Four (4) of these five (5) capacitors numbers 2, 19, 30 and 49 in Figure 17 failed within the first six (6) hours of the test. The fifth capacitor, number 1, failed between 80 and 140 hours of operation in 125°C ambient.

The majority of the capacitors surviving the 1000 hours 85°C ambient test exhibited a small increase in capacitance and a small decrease in dissipation factor is illustrated by the test data in Table B8. Capacitance and dissipation factor data were not obtained after the 370 hour, 125°C ambient test.

4.0 Conclusions

Appreciable size and weight reductions of commutating and load filter capacitors in static inverters may be realized with the use of polycarbonate capacitors instead of paper dielectric capacitors. These potential reductions are attributed to the smaller dissipation factor (i.e. power factor) of polycarbonate capacitors.

Polycarbonate capacitor power losses are quite low between excitation frequencies of 0.4 to 5.0 kilocycles but increase significantly between 5.0 and 50.0 kilocycles. In commutation circuits, capacitor losses may be kept low by reducing resonant frequencies and magnitudes between inductive-capacitive components (L-C ringing.)

Survival of polycarbonate capacitors, from five manufacturers, in the 1000 hour 85°C ambient and 370 hour, 125°C ambient test is encouraging. This type performance suggests that a smaller voltage derating than the 3 to 1 from D.C. to A.C. applications for paper capacitors may be utilized. This voltage derating for AC applications is done to prevent excessive capacitor heating caused by increased capacitor dissipation losses versus frequency.

5.0 Recommendations

Life testing of polycarbonate capacitors should be expanded in quantities of capacitors, voltage levels and temperature levels and renewed in an effort to define the relationship of reliability versus applied voltage, voltage waveform and temperature.

Additional developmental effort, by capacitor manufacturers, to reduce the dissipation factors in the extended frequency range from 10 to 50 kilocycles should be encouraged so that greater static inverter efficiencies may be realized.

Radiation effects testing of polycarbonate capacitors should be accomplished to provide designers of aerospace static inverters capacitor degradation characteristics from radiation encountered in the space environment.

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APPENDIX A

Commutating Capacitor Analyses of Operation and Specification

Analysis of Operation

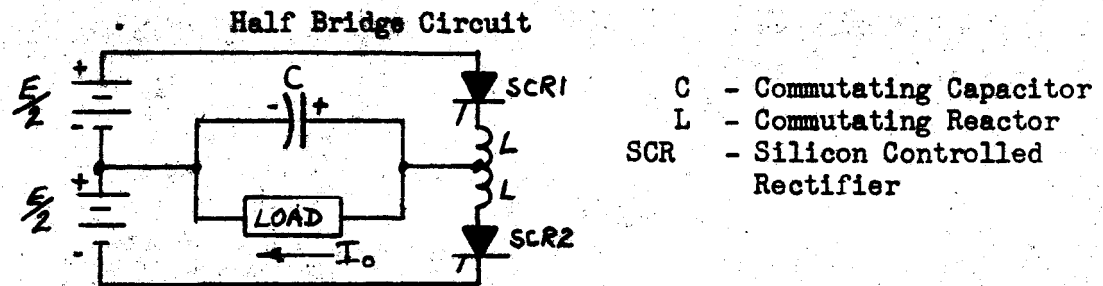


Figure A

Analysis of operation for this circuit is based on these assumptions:

- 1) Inductive load current does not change during the commutation interval.
- 2) Full load turn-off time is one half that at no load.
- 3) When capacitor voltage is zero, turn-off interval is over.

The equivalent circuit shown in Figure B is for the condition when SCR2 has just been triggered into conduction and SCR1 conduction blocked at beginning of commutating interval.

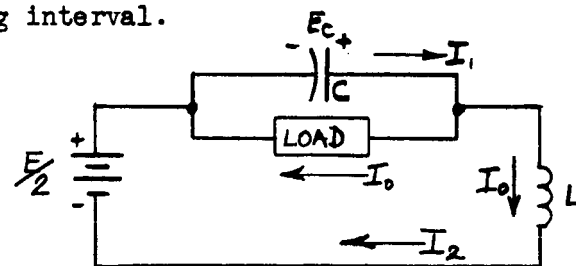


Figure B

Writing the voltage equation for the loop

$$\frac{E}{2} + E_c = \frac{1}{C} \int_0^t i_1(t) dt + L \frac{di_2(t)}{dt} \quad \text{where } t \text{ is turn-off interval,}$$

E_c is the charge on capacitor at start of commutation

Equations describing the equivalent circuit, shown in Figure B, in Laplace notation are:

$$\frac{E}{2s} + \frac{E}{2s} + L I_0 = \frac{I_1(s)}{sC} + I_2(s) sL \quad (1)$$

$$I_2(s) = I_1(s) - \frac{I_0}{s} \quad (2)$$

$$E_c(s) = \frac{E}{2s} - \frac{I_1(s)}{sC} \quad (3)$$

Combining equation (1) and (2) gives

$$\frac{E}{s} + 2L I_0 = I_1(s) \frac{(1 + sL)}{sC} \quad (4)$$

$$I_1(s) = \frac{\frac{E}{s} + 2L I_0}{\frac{1 + sL}{sC}}$$

Substituting equation (4) into equation (3) gives

$$E_c(s) = \frac{E}{2s} - \frac{E}{s(1+LCs^2)} - \frac{2L I_0}{(1+LCs^2)}$$

$$\mathcal{L}^{-1} E_c(s) = E_c(t) = \frac{E}{2} - E(1 - \cos \omega t) - 2L I_0 \omega \sin \omega t \quad (5)$$

$$\text{where } \omega = \sqrt{\frac{1}{LC}}$$

when $E_c = 0$, turn-off interval is over. Solving for t

$$\frac{E}{2} = E \cos \omega t - 2L I_0 \omega \sin \omega t \quad (6)$$

At $I_o = 0$ (no load or current that goes through zero at end of half cycle)

$$E \cos \omega t = \frac{E}{2}; \quad \cos \omega t = .5; \quad \omega t = \pi/3$$

$$t = \pi/3\omega$$

Using the second assumption that turn-off (t_{off}) at full load is one half of t , $t_{off} = \pi/6\omega = \frac{\pi \sqrt{LC}}{6}$

Using t_{off} in equation (6) gives

$$\frac{E}{2} = E \cos \pi/6 - 2 L I_o \omega \sin \pi/6$$

Substituting $1/\sqrt{LC}$ for ω

$$\frac{E}{2} = \frac{E \sqrt{3}}{2} - \frac{L I_o}{\sqrt{LC}} = \frac{E \sqrt{3}}{2} - I_o \sqrt{\frac{L}{C}}$$

$$0.366 E = I_o \sqrt{L/C} \quad (7)$$

To determine the capacitance (C), divide equation (7) by t_{off} , which gives

$$\frac{0.366E}{t_{off}} = \frac{6 I_o}{\pi C}$$

$$C = \frac{5.22 I_o t_{off}}{E} \quad (8)$$

Inductance value (L) may be determined by multiplying equation (7) by t_{off} , which gives

$$L = \frac{0.7 E t_{off}}{I_o} \quad (9)$$

E in equations (8) and (9) are minimum steady state source voltage and I_o is the load current to be commutated at the end of a half cycle.

Capacitance values for circuit configurations shown in Figure A are determined by the minimum steady state voltage levels, I_o and t_{off} of silicon controlled rectifiers listed in Table I.

TABLE I

Silicon Controlled Rectifiers Type	I_o (amps)	t_{off} (usecs)	Minimum Source Voltage Levels		
			25V	50V C(ufds)	90V
G.E. C-11	6	12	15	7.5	4.2
G.E. C-40	16	12	40	20	11.1
G.E. C-55	60	20	250	125	69.0
G.E. C-80	120	25	625	313	174.0

Similar analyses for circuit configurations shown in Figures C and D will yield capacitance values equivalent to one half the values shown in Table I.

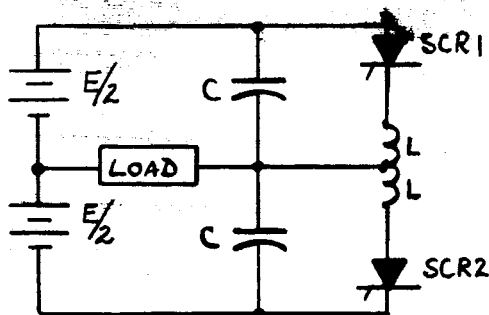


Figure C

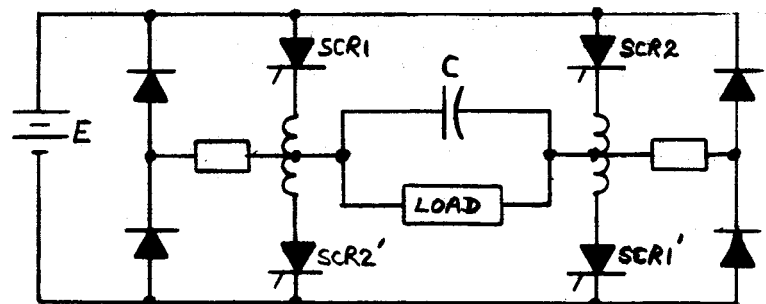


Figure D

Capacitance values, in parallel type inverter configurations, shown in Figure E, are equivalent to one fourth the values of C tabulated in Table I.

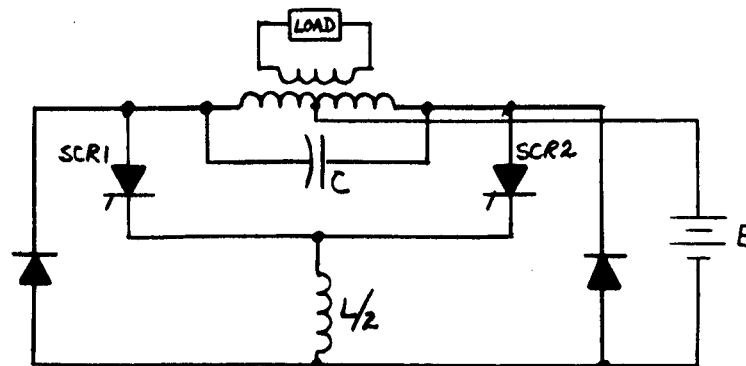


Figure E

Values of commutating capacitances selected for the capacitor survey are 5, 15 and 50 microfarads. Specifications for these capacitors are contained in this appendix. Selection of these values is based on the use of multiple series and parallel capacitor networks for half bridge, full bridge and parallel types of inverters and converters.

Peak recurring capacitor currents are determined as follows.

From energy storage equations

$$\frac{L I_p^2}{2} = \frac{E^2 C}{2}$$

$I_p = E \sqrt{C/L}$, where E is maximum steady state source voltage

Substituting C and L from equations (8) and (9)

$$I_p = 2.74 I_o \frac{E_{\max.}}{E_{\min.}} \text{ for values of } C \quad (10a)$$

$$I_p = 1.37 I_o \frac{E_{\max.}}{E_{\min.}} \text{ for values of } C/2 \quad (10b)$$

Peak recurring capacitor currents for the selected capacitance values are determined from silicon controlled rectifier types, I_o and C values from Table I and are shown in Table II.

TABLE II

Rectifier Type	Voltage Level	Capacitance (ufd)	Capacitor Circuit Configuration	I _{pk} (amps)
C-11	25-35	15	C	23.1
C-40	50-65	10	C/2	28.5
C-80	90-105	50	C	109

ENGINEERING SPECIFICATION

1. Scope--This specification is for an industry survey of capacitors for application in 115/200 volt, 3 phase, 400 cps output static inverters and converters in space environments. The criteria to be used in this survey are:

- A. Volume to capacitance ratio
- B. Weight to capacitance ratio
- C. Power factor to thermal resistance ratio
- D. Volume and weight to energy-storage ratio
- E. Cost to energy-storage ratio

2. Range of Capacitor Ratings

- A. 5 microfarads +20-10% over temperature range

Capacitor No.	1	2	3
Peak Voltage	35	65	105
Peak Voltage (100msec. D.C. Voltage Transient)	52	97	157
Peak Current Amperes at D.C. Working Voltage	4.6	8.6	11
Peak Current and Voltage Waveforms	Fig. A1	Fig. A1	Fig. A1
Peak Current Amperes (100 msec. D.C. Voltage Transient)	6.85	12.8	15.1

- B. 15 microfarads +20-10% over temperature range

Capacitor No.	1	2	3
Peak Voltage	35	65	105
Peak Voltage (100 msec. D.C. Voltage Transient)	52	97	157
Peak Current Amperes at D.C. Working Voltage	13.8	26	33
Peak Current and Voltage Waveforms	Fig. A1	Fig. A1	Fig. A1
Peak Current Amperes (100 msec. D.C. Voltage Transients)	20.5	38.4	49.3

C. 50 microfarads +20-10% over temperature range

Capacitor No.	1	2	3
Peak Voltage	35	65	105
Peak Voltage (100 msec. D.C. Voltage Transient)	52	97	157
Peak Current Ampere at D.C. Working Voltage	46	26	110
Peak Current and Voltage Waveforms	Fig. A1	Fig. A1	Fig. A1
Peak Current Amperes (100 msec. D.C. Voltage Transient)	68	129	165.0

3. Physical Size and Weight--Vendor to recommend optimum size and weight proposed capacitance value and voltage rating.
4. Ambient Temperature-- -55 to +85°C heat sink ambient with a maximum of 125°C capacitor hot spot temperature.
5. Method of Capacitor Power Loss Transfer--Conduction through mounting surface to heat sink ambient.
6. Construction--Hermetically sealed. Capacitor to be subjected to 0.25 atmosphere within equipment enclosure during optional life.
7. Shock--Capacitor is to withstand three 35 g shocks in each direction along the major axes. The applied shocks are half sine waves of 0.008 second duration.
8. Vibration--While energized, capacitor is to withstand the following sinusoidal vibration requirements:

Frequency	Force or Displacement
5-20	0.3 inches D.A.
20-100	5 g's
100-500	10 g's
500-2000	15 g's

Duration of the applied vibrational forces is four 15-minute logarithmic sweeps from 5-2000-5 cps at the specified levels and 10-minute dwells at each resonant frequency found during the sweeps.

9. Radiation--Capacitor shall have a tolerance to the following integrated radiation dosage without malfunction:
 - A. 5×10^{12} NVT Fast Neutrons/cm²
 - B. 5×10^7 RADS (Carbon) Gamma Rays
10. Operational Life Objective--Energized for 3 years continuously while exposed to the radiation listed in 9 above and 85°C heat sink temperature. Capacitor to remain within capacitance tolerance.

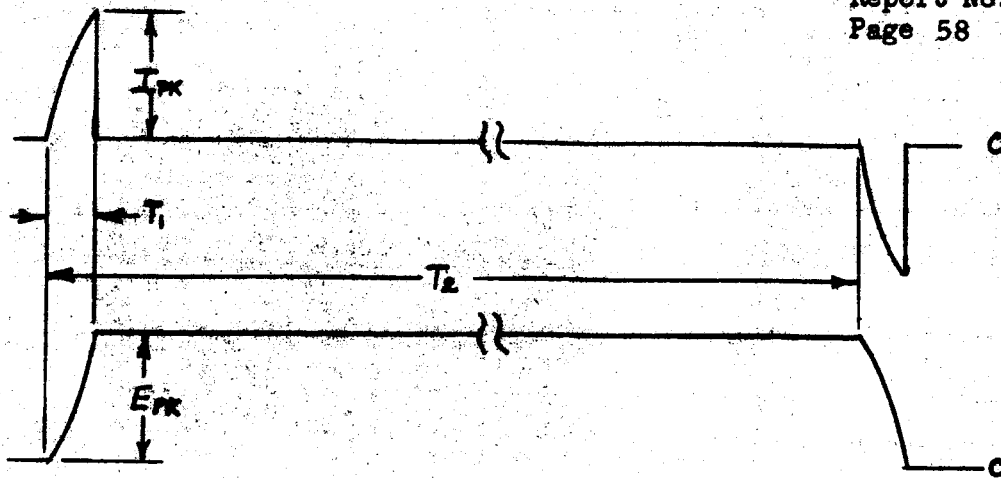


FIGURE A-1

PEAK CURRENT AND VOLTAGE WAVEFORMS

FIGURE A-1 $T_1 = 74.5$ microseconds
 $T_2 = 1256$ microseconds

Capacitance and Dissipation Factor Test Data

Data contained in Tables B1 through B3 were obtained by bridge measurements and calorimeter data in 25°C ambient with sinusoidal voltage waveforms.

Data contained in Tables B4 through B6 were obtained by bridge measurements over the temperature range of -55°C to +85°C and frequency range from 0.4 to 10.0 kilocycles. Electrolytic capacitor test data contained in Table B7 were obtained by bridge measurements over the temperature range from -55°C to +85°C and 120 to 1200 cps frequency range.

Life test capacitor data contained in Table B8 were obtained by bridge measurements before and after the 1000 hour test in 85°C ambient. These data were taken in 25°C ambient with a test frequency of 1 kilocycle.

An example of the dissipation factor corrections applied to the bridge data is given below:

From Table A1, capacitor No. 1A, the dissipation factor as determined from the bridge data at 10 kilocycles is 1.110%. As measured with the calorimeter, the dissipation factor at 10 kilocycles is 0.975%.

By ratio of the bridge data of the dissipation factor for capacitor number 1B and 1A, the corrected dissipation factor for capacitor 1B at 10 kilocycles is:

$$\frac{.958\%}{1.110\%} \times .975 = .840\%$$

25°C TEST DATA FOR
METALLIZED POLYCARBONATE CAPACITORS

SINUSOIDAL VOLTAGE										CORRECTED BRIDGE											
CALCULATED FROM BRIDGE MEASUREMENTS										CALCULATED FROM CALORIMETER DATA											
FREQUENCY (KC)	C (MFD)					DF (%)					DF (%)					CAPACITOR RATING					
	4	1	3	5	10	4	1	3	5	10	4	1	3	5	10						
1A	.965	.980	.983	.984	.991	.731	.361	.408	.581	1.110	.142	.151	.222	.400	.975	-	-	-	-	-	1 MFD, 400 VDC
1B	.970	.984	.986	.988	.998	.671	.316	.367	.507	.958	-	-	-	-	-	.130	.132	.198	.343	.840	
1C	.981	.995	.999	1.000	1.010	.660	.330	.366	.525	.971	-	-	-	-	-	.128	.138	.199	.362	.852	
1D	.952	.965	.967	.969	.975	.676	.353	.379	.540	1.020	-	-	-	-	-	.131	.148	.206	.372	.895	
1E	.950	.963	.966	.967	.952	.690	.361	.428	.614	1.160	-	-	-	-	-	.134	.151	.233	.424	1.020	
2A	2.179	2.192	2.198	2.206	2.238	.529	.346	.537	.844	1.650	-	-	-	-	-	.095	.124	.209	.318	.790	2 MFD 400 VDC
2B	2.183	2.195	2.201	2.207	2.238	.555	.430	.797	1.280	2.500	-	-	-	-	-	.100	.154	.312	.482	1.200	
2C	2.170	2.191	2.187	2.194	2.211	.536	.387	.646	1.030	2.040	-	-	-	-	-	.096	.138	.252	.388	.975	
2D	2.203	2.216	2.222	2.229	2.263	.509	.348	.558	.874	1.710	-	-	-	-	-	.092	.124	.218	.330	.818	
2E	2.140	2.153	2.159	2.166	2.197	.579	.499	1.000	1.620	3.280	.104	.178	.390	.610	1.570	-	-	-	-	-	
3A	2.683	2.688	2.703	2.712	2.763	.503	.340	.569	.904	1.810	-	-	-	-	-	.166	.178	.363	.577	1.240	2.5 MFD 400 VDC
3B	2.668	2.686	2.689	2.690	2.703	.682	.837	2.040	3.250	5.830	-	-	-	-	-	.225	.436	1.300	2.060	3.980	
3C	2.639	2.651	2.658	2.668	2.718	.503	.348	.369	.893	1.770	-	-	-	-	-	.166	.183	.233	.569	1.215	
3D	2.672	2.688	2.690	2.700	2.739	.637	.708	1.680	2.750	5.470	.210	.370	1.070	1.750	3.740	-	-	-	-	-	
3E	2.649	2.662	2.671	2.681	2.731	.489	.354	.607	.965	1.890	-	-	-	-	-	.162	.186	.306	.613	1.292	
5A	1.920	1.934	1.940	1.947	1.971	.525	.336	.490	.744	1.470	-	-	-	-	-	.094	.134	.191	.280	.703	2 MFD 400VDC
5B	1.945	1.956	1.961	1.967	1.992	.531	.332	.479	.726	1.410	-	-	-	-	-	.095	.132	.187	.274	.675	
5C	1.916	1.931	1.936	1.941	1.967	.590	.343	.484	.736	1.470	-	-	-	-	-	.105	.136	.189	.277	.703	
5D	1.949	1.963	1.968	1.974	2.001	.530	.337	.502	.773	1.510	-	-	-	-	-	.095	.134	.196	.291	.723	
5E	1.950	2.002	2.006	2.012	2.040	.530	.332	.492	.753	1.450	-	-	-	-	-	.095	.132	.192	.283	.693	
6A	1.970	1.981	1.986	1.991	2.017	.544	.390	.611	.943	1.890	-	-	-	-	-	.098	.139	.238	.355	.907	2 MFD 300 VDC
6B	1.956	1.967	1.972	1.977	2.003	.519	.388	.409	.740	1.380	-	-	-	-	-	.093	.121	.191	.278	.662	
6C	1.910	1.923	1.927	1.938	1.951	.549	.379	.582	.882	1.350	-	-	-	-	-	.099	.135	.227	.382	.669	
6D	2.008	2.020	2.025	2.031	2.060	.547	.395	.620	1.010	1.980	-	-	-	-	-	.098	.141	.254	.380	.951	
6E	1.953	1.965	1.970	1.974	2.004	.551	.381	.591	.913	1.790	-	-	-	-	-	.099	.136	.231	.343	.860	

TABLE BI

25°C TEST DATA FOR METALLIZED

POLYCARBONATE CAPACITORS

SINUSOIDAL VOLTAGE
CALCULATED FROM
CALORIMETER DATA

CORRECTED BRIDGE

CALCULATED FROM BRIDGE MEASUREMENTS

FREQUENCY (Kc)	C (MFD)										DF(%)										CAPACITOR RATING																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																															
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25°C TEST DATA FOR
POLYCARBONATE/FOIL CAPACITORS

CORRECTED BRIDGE																						
SINUSOIDAL VOLTAGE CALCULATED FROM CALORIMETER DATA																						
CALCULATED FROM BRIDGE MEASUREMENTS																						
FREQUENCY (KC)	CAPACITOR No.	C (MFD)										DF (%)										
		.4	1	3	5	10	.4	1	3	5	10	.4	1	3	5	10	.4	1	3	5	10	
9A		.842	.856	.857	.858	.864	.719	.310	.296	.422	.763	-	-	-	-	-	.108	.056	.084	.104	.234	1 MFD 400 VDC
9B		.840	.852	.855	.856	.861	.712	.306	.292	.401	.763	.107	.055	.083	.101	.234	-	-	-	-	-	
9C		.842	.858	.860	.861	.867	.708	.338	.303	.415	.774	-	-	-	-	-	.106	.061	.086	.106	.237	
9D		.841	.856	.858	.859	.865	.695	.323	.294	.412	.774	-	-	-	-	-	.104	.058	.084	.104	.237	
9E		.839	.857	.859	.860	.866	.692	.316	.298	.412	.773	-	-	-	-	-	.104	.057	.085	.104	.236	
10A		1.967	1.910	1.985	1.991	2.019	.503	.332	.523	.821	1.660	.057	.055	.116	.140	.226	-	-	-	-	-	
10B		1.972	1.984	1.990	1.995	2.024	.499	.330	.526	.821	1.690	-	-	-	-	-	.056	.055	.116	.140	.230	
10C		1.973	1.986	1.991	1.997	2.025	.499	.327	.519	.813	1.650	-	-	-	-	-	.056	.054	.115	.138	.225	
10D		1.973	1.985	1.991	1.997	2.024	.502	.332	.526	.823	1.670	-	-	-	-	-	.057	.055	.116	.140	.227	
10E		1.968	1.981	1.985	1.992	2.020	.506	.329	.518	.811	1.650	-	-	-	-	-	.057	.054	.115	.139	.225	
11A		3.094	3.108	3.117	3.131	3.200	.480	.367	.665	1.110	2.310	.052	.038	.068	.102	.202	-	-	-	-	-	
11B		3.097	3.059	3.069	3.082	3.150	.489	.385	.751	1.250	2.590	-	-	-	-	-	.053	.040	.073	.116	.227	
11C		2.950	2.963	2.972	2.985	3.048	.481	.365	.665	1.080	2.260	-	-	-	-	-	.052	.038	.065	.100	.198	
11D		3.085	3.097	3.107	3.121	3.193	.495	.377	.720	1.160	2.420	-	-	-	-	-	.054	.039	.070	.108	.212	
11E		3.006	3.018	3.028	3.043	3.107	.496	.379	.694	1.140	2.400	-	-	-	-	-	.054	.039	.068	.106	.210	
17A		5.570	5.600	5.630	5.680	5.880	.498	.457	.843	1.365	3.200	-	-	-	-	-	.085	.097	.152	.236	.444	5 MFD 157 VDC
17B		5.448	5.460	5.486	5.536	5.784	.516	.366	.666	1.530	3.540	-	-	-	-	-	.088	.082	.120	.265	.490	
18A		3.198	3.214	3.225	3.256	3.417	.737	.735	1.560	2.520	5.130	.134	.153	.189	.214	.422	-	-	-	-	-	3 MFD 135 VAC
18B		3.279	3.301	3.323	3.339	3.443	.543	.445	.790	1.230	1.390	-	-	-	-	-	.093	.092	.094	.104	.278	
19A		4.650	4.660	4.690	4.710	4.880	.468	.362	.662	1.080	2.000	-	-	-	-	-	-	-	-	-	-	
19B		4.680	4.680	4.690	4.720	4.900	.428	.324	.653	1.090	2.540	-	-	-	-	-	.073	.072	.113	.189	.352	
19C		4.650	4.660	4.680	4.700	4.870	.389	.314	.635	1.070	2.470	-	-	-	-	-	.063	.070	.110	.185	.345	
19D		4.650	4.670	4.680	4.720	4.900	.411	.325	.648	1.060	2.530	-	-	-	-	-	.075	.072	.112	.189	.350	
19E		4.660	4.640	4.710	4.740	4.840	.378	.309	.659	1.080	2.550	-	-	-	-	-	.065	.069	.110	.187	.353	

TABLE B2

25°C TEST DATA FOR

METALLIZED PAPER CAPACITORS

SINUSOIDAL VOLTAGE
CALCULATED FROM
CALORIMETER DATA

CORRECTED BRIDGE

CALCULATED FROM BRIDGE MEASUREMENTS

FREQUENCY (KC)	CAPACITOR NO.	C (MFD)					LF (%)					DF (%)					CAPACITOR RATING		
		.4	1	3	5	10	.4	1	3	5	10	.4	1	3	5	10			
4A		1.838	1.843	1.839	1.849	1.855	1.170	1.030	1.325	1.630	2.520	-	-	.351	.248	.440	.460	1.115	
4B		1.847	1.850	1.848	1.849	1.867	1.320	1.030	1.360	1.740	2.730	-	-	.396	.248	.455	.490	1.205	
4C		1.933	1.939	1.934	1.935	1.951	1.170	1.100	1.570	2.110	3.490	-	-	.351	.266	.524	.596	1.545	
4D		1.865	1.871	1.867	1.868	1.886	1.130	1.010	1.290	1.620	2.460	-	-	.338	.244	.431	.457	1.090	
4E		1.859	1.864	1.859	1.860	1.877	1.120	1.010	1.310	1.650	2.550	-	-	.336	.244	.438	.465	1.127	
7A		1.863	1.871	1.870	1.871	1.889	.917	.793	1.050	1.370	2.160	.275	.192	.351	.386	.955	-	-	
7B		1.848	1.856	1.853	1.856	1.875	.905	.776	1.030	1.340	2.170	-	-	.271	.188	.345	.378	.960	
7C		1.858	1.868	1.866	1.869	1.887	.906	.768	1.020	1.320	2.090	-	-	.272	.186	.341	.372	.925	
7D		1.852	1.860	1.858	1.859	1.878	.912	.782	1.030	1.340	2.170	-	-	.274	.184	.345	.378	.960	
7E		1.862	1.870	1.868	1.871	1.889	.917	.788	1.050	1.360	2.160	-	-	.275	.191	.351	.384	.955	
8A		2.175	2.181	2.178	2.184	2.217	1.010	.908	1.250	1.640	2.730	-	-	.302	.220	.417	.462	1.205	
8B		2.160	2.167	2.163	2.167	2.193	1.000	.899	1.220	1.630	2.710	-	-	.300	.218	.408	.462	1.200	
8C		2.164	2.171	2.169	2.170	2.199	1.020	.914	1.240	1.620	2.700	-	-	.306	.221	.414	.462	1.198	
8D		2.183	2.189	2.186	2.188	2.215	1.010	.908	1.250	1.660	2.750	-	-	.302	.220	.417	.468	1.215	
8E		2.161	2.167	2.164	2.167	2.195	1.050	.937	1.270	1.820	2.730	-	-	.315	.226	.424	.512	1.205	
16A		2.908	2.911	2.891	2.898	2.935	1.310	1.280	1.610	1.970	3.000	-	-	.697	.869	1.100	1.230	1.610	
16B		2.916	2.918	2.907	2.910	2.957	1.240	1.180	1.500	1.860	2.950	-	-	.660	.801	1.040	1.160	1.580	
16C		2.909	2.909	2.892	2.894	2.940	1.310	1.280	1.630	2.000	3.070	.697	.870	1.125	1.250	1.650	-	-	
16D		2.937	2.937	2.924	2.931	2.977	1.290	.750	1.590	1.970	3.030	-	-	.686	.509	1.100	1.230	1.630	
16E		2.908	2.908	2.898	2.898	2.945	1.260	1.220	1.550	1.920	2.980	-	-	.670	.828	1.070	1.200	1.600	

TABLE B3

CAPACITOR TEST DATA VERSUS TEMPERATURE
FOR METALLIZED POLYCARBONATE CAPACITORS

CAPACITOR RATING
C MFD V DC
CORRECTED BRIDGE
DF %

FREQUENCY SINUSOIDAL (KC)	CAPACITOR NO.	CALCULATED FROM BRIDGE MEASUREMENTS					CORRECTED BRIDGE					CAPACITOR RATING					AMBIENT TEMPERATURE
		4	1	3	5	10	4	1	3	5	10	C MFD	V DC				
+85°C																	
1A	1A	975	987	990	993	1008	688	449	657	1000	2000	1.32	140	221	407	1035	1 400
2E	2E	2.155	2.166	2.175	2.187	2.248	.724	.876	2.210	3.660	7.610	.108	.194	.447	.702	1.800	2 400
3D	3D	2.617	2.632	2.641	2.657	2.725	.792	.1120	2.920	4.830	9.650	.209	.394	.1125	1.850	3.950	2.5 400
5E	5E	1.989	2.002	2.004	2.010	2.083	.554	.456	.915	1.520	3.030	.092	.128	.192	.290	.702	2 400
6C	6C	1.890	1.931	1.937	1.947	1.997	.548	.470	.969	1.580	3.300	.091	.128	.228	.355	.737	2 300
12A	12A	3.019	3.019	3.061	3.088	3.229	.598	.634	1.480	3.110	5.370	.055	.096	.186	.361	.530	3 200
13C	13C	3.102	3.114	3.132	3.163	3.305	.680	.639	1.480	2.500	5.440	.064	.100	.198	.311	.573	3 200
14A	14A	2.783	2.793	2.806	2.829	2.936	.596	.626	1.440	2.390	5.080	.060	.100	.182	.278	.444	3 200
15B	15B	3.041	3.057	3.073	3.101	3.244	.735	.1020	2.730	4.630	9.970	.059	.111	.234	.356	.669	3 200
+25°C																	
1A	1A	965	977	982	982	992	.743	.485	.659	981	1.900	.142	.151	.222	.400	.975	1 400
2E	2E	2.140	2.152	2.157	2.174	2.233	.694	.804	1.930	3.180	6.630	.104	.178	.390	.610	1.570	2 400
3D	3D	2.602	2.614	2.634	2.701	2.773	.798	.1080	2.780	4.570	9.140	.210	.370	1.070	1.750	3.740	2.5 400
5E	5E	1.982	2.002	2.009	2.020	2.076	.574	.471	.912	1.480	2.990	.095	.132	.192	.283	.693	2 400
6C	6C	1.912	1.922	1.929	1.938	1.988	.593	.490	.961	1.480	2.980	.094	.135	.227	.332	.669	2 300
12A	12A	3.011	3.022	3.031	3.046	3.109	.476	.378	.706	1.105	2.420	.055	.096	.187	.290	.525	3 200
13C	13C	3.182	3.194	3.203	3.218	3.242	.515	.431	.827	1.330	2.750	.059	.109	.219	.336	.597	3 200
14A	14A	2.771	2.783	2.791	2.802	2.854	.516	.377	.642	1.020	2.110	.060	.096	.170	.258	.458	3 200
15B	15B	3.042	3.056	3.065	3.080	3.143	.500	.402	.969	1.240	2.610	.057	.102	.204	.313	.566	3 200
-25°C																	
1A	1A	962	969	975	977	990	.758	.574	.873	1.290	2.390	.144	.179	.294	.523	1.280	1 400
2E	2E	2.148	2.148	2.148	2.158	2.216	.815	.1030	2.450	3.940	8.000	.121	.228	.445	.757	1.895	2 400
3D	3D	2.671	2.678	2.683	2.698	2.778	.930	.1190	2.780	4.460	8.800	.245	.408	1.070	1.710	3.600	2.5 400
5E	5E	1.979	1.990	1.994	2.001	2.056	.709	.626	1.080	1.630	3.180	.118	.175	.227	.312	.738	2 400
6C	6C	1.901	1.912	1.915	1.920	1.970	.721	.638	1.100	1.650	3.110	.120	.176	.259	.370	.698	2 300
12A	12A	2.998	2.998	3.014	3.039	3.169	.652	.671	1.420	2.350	4.740	.060	.102	.178	.261	.467	3 200
13C	13C	3.179	3.188	3.197	3.226	3.315	.630	.233	2.06	2.870	5.590	.059	.063	.275	.357	.590	3 200
14A	14A	2.757	2.771	2.778	2.797	2.894	.934	.685	1.390	2.200	4.570	.053	.109	.175	.256	.438	3 200
15B	15B	3.033	3.042	3.055	3.081	3.24	.959	.1380	3.430	5.600	11.550	.077	.150	.293	.441	.775	3 200
-55°C																	
1A	1A	951	965	966	969	980	.898	.708	930	1.260	2.180	.171	.220	.314	.513	1.120	1 400
2E	2E	2.118	2.127	2.139	2.139	2.193	1.690	3.010	7.980	13.080	24.610	.253	.618	1.610	2.510	6.300	2 400
3D	3D	2.649	2.659	2.662	2.678	2.757	.990	1.210	2.680	4.260	8.420	.261	.414	1.030	1.630	3.450	2.5 400
5E	5E	1.965	1.975	1.979	1.997	2.040	.818	.763	1.270	1.840	3.250	.135	.214	.267	.357	.753	2 400
6C	6C	1.887	1.896	1.900	1.908	1.952	.806	.678	1.230	1.790	3.360	.134	.190	.290	.402	.753	2 300
12A	12A	2.973	2.978	2.988	3.006	3.137	.796	.858	1.610	2.470	4.750	.073	.130	.202	.287	.468	3 200
13C	13C	3.157	3.175	3.175	3.202	3.346	1.320	2.150	2.060	2.910	5.680	.594	.335	.275	.362	.597	3 200
14A	14A	2.746	2.754	2.761	2.774	2.876	.765	.748	1.460	2.230	4.430	.077	.119	.183	.259	.431	3 200
15B	15B	3.015	3.025	3.034	3.057	3.185	2.06	3.980	10.900	18.120	37.600	.162	.434	.934	1.430	2.520	3 200

DIFFERENCE IN CAPACITANCE BETWEEN TEMPERATURES
FOR CAPACITANCE/FOR CAPACITORS

CALCULATED FROM BRIDGE MEASUREMENTS

FREQUENCY SINUSOIDAL (KC)	CAPACITOR NO.	C MFD										DF %					DF %					CAPACITOR RATING			AMBIENT TEMPERATURE
																						C MFD	V DC	V AC 400W	
		4	1	3	5	10	4	1	3	5	10	4	1	3	5	10									
9A		847	859	862	865	874	683	384	465	702	1280	107	053	077	101	210				1	400		+85°C		
10A		1976	1990	1997	2002	2059	584	584	1290	2150	4360	054	050	108	132	212				2	200				
11A		3058	3073	3092	3124	3269	595	589	1380	2310	5110	053	035	063	096	197				3		135			
17A		5406	5436	5536	5636	6148	747	907	2190	3546	8900	084	097	136	207	415				5	157				
18A		3219	3239	3259	3289	3430	693	675	1370	2480	5490	126	141	166	210	457				3		135			
19A		4503	4523	4563	4623	4944	572	596	1790	3060	6750	074	061	107	169	246				5	105				
9A		843	854	857	859	869	690	402	505	746	1430	108	056	084	104	234				1	400		+25°C		
10A		1968	1979	1987	2000	2046	618	622	1380	2270	4640	057	055	116	140	226				2	200				
11A		3089	3103	3120	3150	3305	587	632	1480	2460	5260	052	038	068	102	202				3		135			
17A		5570	5600	5630	5680	5880	757	970	2450	4030	9520	085	097	152	236	444				5	157				
18A		3198	3214	3225	3256	3417	737	735	1560	2520	5130	134	153	189	214	442				3		135			
19A		4650	4660	4690	4710	4880	468	362	1662	1080	2000	080	081	119	187	277				5	105				
9A		839	851	852	855	862	794	539	528	859	1520	124	075	088	119	251				1	400		-25°C		
10A		1959	1965	1975	1985	2032	827	1020	2330	3740	7500	076	073	196	230	366				2	200				
11A		3096	3105	3120	3147	3293	683	722	1500	2390	4990	061	043	063	097	192				3		135			
17A		5406	5416	5436	5526	5997	1080	1230	2400	3930	8870	122	123	149	230	412				5	157				
18A		3162	3172	3178	3206	3453	1030	1020	1790	2550	5070	187	212	216	217	415				3		135			
19A		4553	4573	4603	4663	4984	692	803	1800	2910	6120	090	083	107	161	223				5	105				
9A		835	835	846	847	854	934	694	823	1040	1680	146	097	137	144	276				1	400		-55°C		
10A		1947	1957	1959	1966	2011	1750	3130	8350	13800	27700	162	276	702	853	1352				2	200				
11A		3089	3097	3109	3136	3282	803	837	1700	2630	5190	072	050	078	110	200				3		135			
17A		5336	5345	5366	5455	5916	1090	1210	2310	3770	8540	123	121	142	221	397				5	157				
18A		3123	3131	3140	3165	3304	1210	1020	1720	2570	5010	220	212	208	218	461				3		135			
19A		4553	4563	4590	4653	4964	832	1040	2330	3700	6260	108	107	129	205	329				5	105				

TABLE B5

CAPACITOR TEST DATA VERSUS TEMPERATURE

FOR METALLIZED PAPER CAPACITORS

CALCULATED CAP BRIDGE MEASUREMENTS CORRECTED BRIDGE

FREQUENCY SINUSOIDAL (KC)		C (MFD)										DF (%)										CAPACITOR RATING				AMBIENT TEMPERATURE																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																	
		4	1	3	5	10	4	1	3	5	10	4	1	3	5	10																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																											

TABLE B6

CAPACITOR TEST DATA VERSUS TEMPERATURE
FOR TANTALUM ELECTROLYTIC CAPACITORS

BRIDGE MEASUREMENTS

FREQUENCY CAPACITOR NO.	C (MFD)			DF %			TYPE	RATING		CAP. NO.	ΔC % VS. REF. TEMP.	AMBIENT TEMPERATURE
	120 CPS	800 CPS	1200 CPS	120 CPS	800 CPS	1200 CPS		MFD	VDC			
20A	38.75	38.52	38.42	1.34	.83	.80	S.T.	43	70	20A	53.8	+85 °C
20B	40.47	40.25	40.23	1.25	.75	.73	S.T.	43	70	20B	59.6	
20C	39.59	39.31	39.30	1.48	.88	.86	S.T.	43	70	20C	46.6	
20D	42.51	42.07	42.03	1.48	.77	.74	S.T.	43	70	20D	44.2	
20E	40.08	39.33	39.74	1.42	.89	.87	S.T.	43	70	20E	53.6	
21A	44.11	43.22	43.13	2.17	.89	.82	F.T.	36	150	21A	28.5	
21B	39.30	38.68	38.45	2.47	.86	.81	F.T.	36	150	21B	27.0	
21C	41.83	40.77	40.52	2.76	.96	.88	F.T.	36	150	21C	29.8	
21D	42.08	41.27	41.00	2.35	.88	.77	F.T.	36	150	21D	27.6	
20H	38.25	37.77	37.64	2.32	.72	.66	S.T.	43	70			+26 °C
20B	39.89	39.65	39.56	2.00	.58	.54	S.T.	43	70			
20C	38.92	38.56	38.44	2.42	.83	.78	S.T.	43	70			
20D	41.74	41.35	41.19	2.16	.79	.74	S.T.	43	70			
20E	39.54	39.05	38.92	2.86	2.24	2.21	S.T.	43	70			
21A	42.45	41.77	41.55	2.10	1.08	1.00	F.T.	36	150			
21B	37.80	37.23	37.10	2.09	1.02	.97	F.T.	36	150			
21C	40.14	39.21	39.00	2.81	1.13	1.04	F.T.	36	150			
21D	40.69	39.68	39.33	2.81	1.08	.92	F.T.	36	150			
20A	37.21	35.55	34.15	8.94	7.65	7.31	S.T.	43	70			-25 °C
20B	37.02	37.24	35.74	8.67	7.45	7.06	S.T.	43	70			
20C	38.06	36.07	34.50	9.57	8.25	7.56	S.T.	43	70			
20D	40.62	39.31	38.00	7.90	6.92	6.71	S.T.	43	70			
20E	38.35	35.40	33.50	11.48	9.81	8.88	S.T.	43	70			
21A	40.85	39.27	38.55	4.54	3.10	2.90	F.T.	36	150			
21B	36.39	34.85	34.19	4.45	2.86	2.64	F.T.	36	150			
21C	38.29	36.38	35.55	5.23	3.03	2.80	F.T.	36	150			
21D	38.09	36.65	36.18	5.22	2.73	2.56	F.T.	36	150			
20A	35.98	24.83	17.90	36.94	19.32	19.30	S.T.	43	70			-55 °C
20B	37.60	23.75	16.45	34.99	18.75	17.32	S.T.	43	70			
20C	36.58	25.15	21.10	40.18	22.91	17.38	S.T.	43	70			
20D	39.51	28.49	23.72	33.04	21.44	16.36	S.T.	43	70			
20E	36.42	22.57	18.22	49.27	23.70	17.90	S.T.	43	70			
21A	37.15	33.93	31.52	16.15	10.85	9.70	F.T.	36	150			
21B	34.72	30.39	28.71	14.87	9.83	8.70	F.T.	36	150			
21C	36.34	31.24	29.38	15.85	10.07	8.75	F.T.	36	150			
21D	36.17	32.40	30.45	14.83	10.33	9.32	F.T.	36	150			

S.T. SINTERED TANTALUM
F.T. FOIL TANTALUM

TABLE B7

1 CAPACITOR TEST DATA

BEFORE AND AFTER LIFE TEST

100 AMP 60 HZ @ 1 K-CYCLE TEST CONDITIONS

BEFORE LIFE TEST				AFTER LIFE TEST				BEFORE LIFE TEST				AFTER LIFE TEST							
CAP. No.	BRIDGE MEAS.		CORRECTED DF (%)	CAP. TYPE	CAP. No.	BRIDGE MEAS.		CORRECTED DF (%)	CAP. No.	BRIDGE MEAS.		CORRECTED DF (%)	CAP. No.	BRIDGE MEAS.		CORRECTED DF (%)			
	C (MFD)	DF (%)				C (MFD)	DF (%)			C (MFD)	DF (%)			C (MFD)	DF (%)		C (MFD)	DF (%)	
1B	.984	.316	.132	MPC	1B	.977	.326	.115	MPC	15E	2.991	.803	.203	MPC	15E	3.000	.428	.108	MPC
1C	.995	.330	.138	MPC	1C	.988	.325	.136	MPC	10D	1.985	.332	.055	PCF	10D	2.005	.271	.045	PCF
1D	.965	.353	.148	MPC	1D	.987	.327	.137	MPC	11C	2.983	.365	.038	PCF	11C	2.962	.287	.030	PCF
1E	.963	.361	.151	MPC	1E	.957	.344	.144	MPC	11D	3.097	.377	.039	PCF	11D	3.104	.311	.032	PCF
3A	2.688	.340	.178	MPC	3A	2.713	.323	.162	MPC	11E	3.018	.379	.039	PCF	11E	3.020	.301	.031	PCF
3E	2.686	.354	.186	MPC	3E	2.680	.322	.169	MPC	17B	5.470	.365	.082	PCF	17B	5.500	.452	.102	PCF
5A	1.934	.336	.134	MPC	5A	1.925	.303	.121	MPC	18B	3.310	.445	.092	PCF	18B	3.334	.428	.088	PCF
5B	1.956	.332	.132	MPC	5B	1.947	.310	.123	MPC	4C	1.939	1.100	.266	MP	4C	1.958	1.132	.273	MP
5C	1.931	.343	.136	MPC	5C	1.922	.304	.121	MPC	4D	1.871	1.010	.244	MP	4D	1.985	.971	.239	MP
5D	1.963	.337	.134	MPC	5D	1.955	.308	.122	MPC	4E	1.864	1.010	.244	MP	4E	1.879	.991	.226	MP
5E	2.002	.332	.132	MPC	5E	1.995	.313	.124	MPC	7B	1.856	.776	.188	MP	7B	1.873	.770	.186	MP
6A	1.981	.390	.139	MPC	6A	2.003	.401	.143	MPC	7C	1.868	.768	.186	MP	7C	1.885	.744	.180	MP
6C	1.923	.379	.135	MPC	6C	1.943	.379	.138	MPC										
6E	1.965	.381	.136	MPC	6E	1.983	.370	.132	MPC										
12E	3.008	.366	.093	MPC	12E	3.020	.352	.089	MPC										
13A	3.277	.456	.116	MPC	13A	3.307	.360	.091	MPC										
13B	3.274	.437	.111	MPC	13B	3.309	.356	.091	MPC										
13C	3.194	.431	.109	MPC	13C	3.226	.341	.086	MPC										
13D	3.268	.440	.112	MPC	13D	3.280	.348	.088	MPC										
13E	3.219	.435	.110	MPC	13E	3.255	.347	.088	MPC										
14A	2.783	.377	.096	MPC	14A	2.813	.363	.092	MPC										
14C	2.721	.370	.094	MPC	14C	2.736	.350	.089	MPC										
14E	2.714	.442	.112	MPC	14E	2.806	.427	.108	MPC										
15B	3.056	.402	.102	MPC	15B	3.067	.362	.092	MPC										
15D	3.039	.802	.203	MPC	15D	3.047	.443	.112	MPC										

TABLE B8